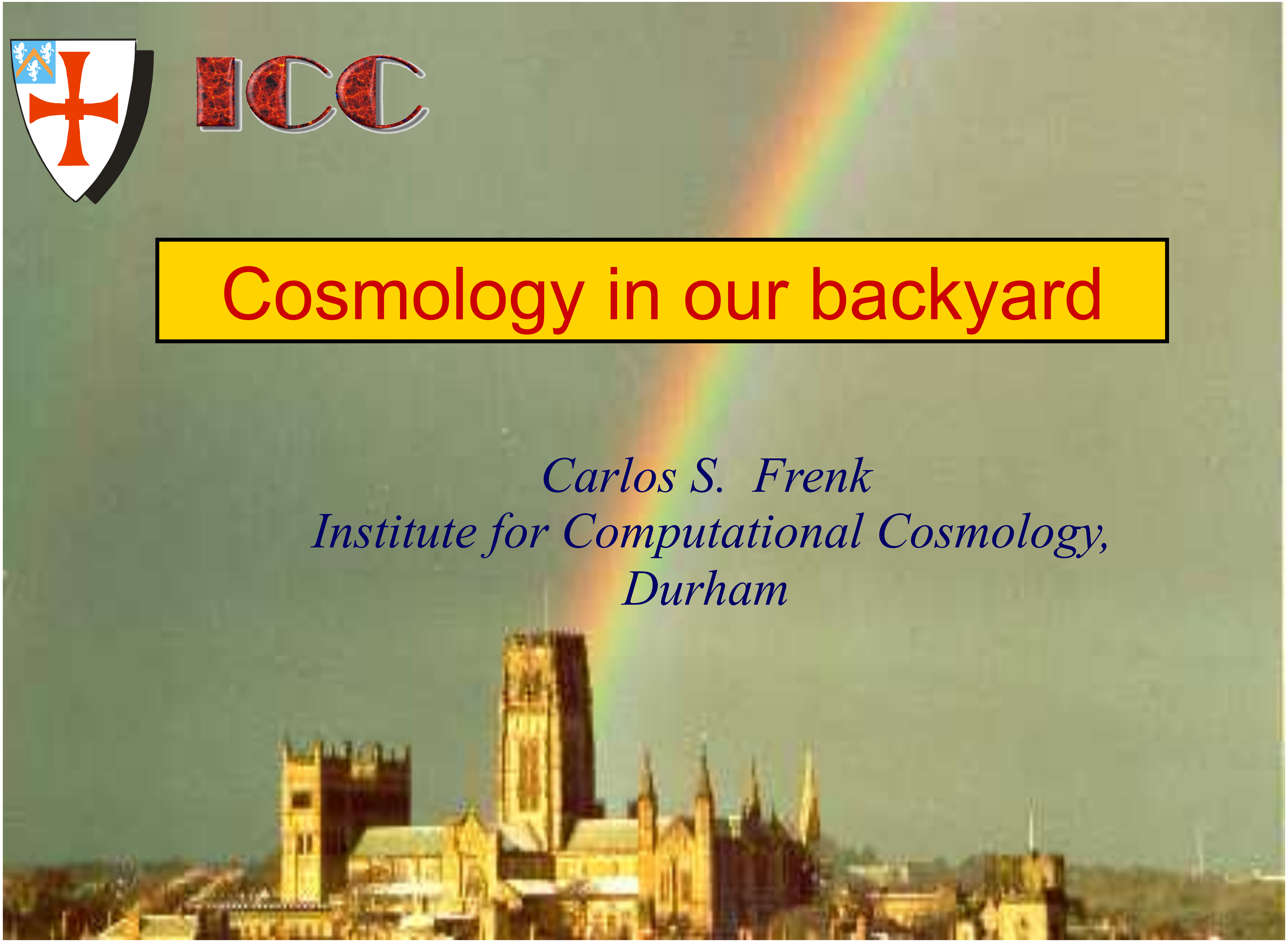


# Cosmology in our backyard

*Carlos S. Frenk*
*Institute for Computational Cosmology,*
*Durham*

# The cold dark matter model

## Detecting cold dark matter

If CDM is a supersymmetric particle, 3 possibilities

- From evidence for SUSY at LHC
- Direct detection (underground labs)
- Indirect detection through annihilation radiation (e.g. $\gamma$ rays)

If CDM is an axion:

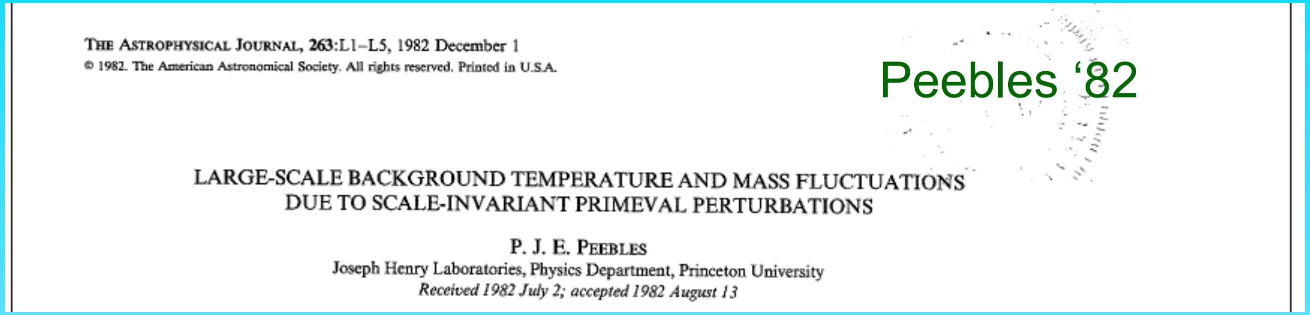
- Direct detection in resonant magnetic cavity

# The cold dark matter model

How likely is it that the CDM hypothesis is correct?

(from an astrophysical point of view)

# The cold dark matter cosmogony



Peebles '82

THE ASTROPHYSICAL JOURNAL, 263:L1–L5, 1982 December 1
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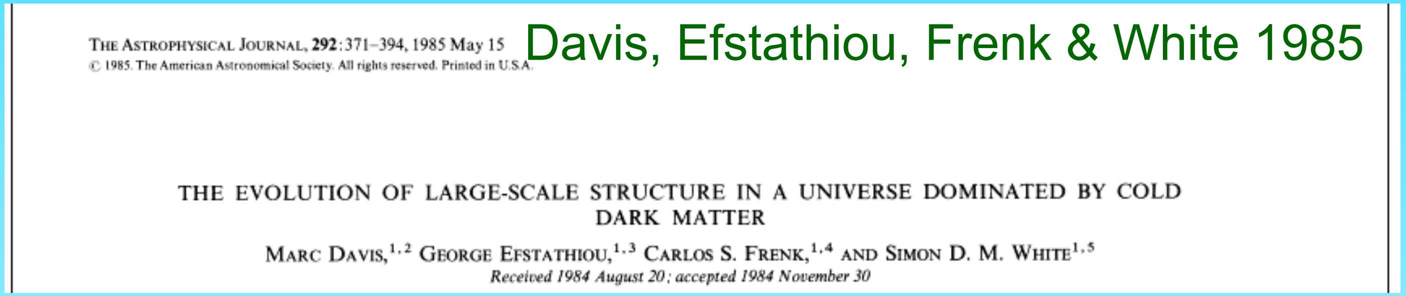
LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

P. J. E. PEEBLES
Joseph Henry Laboratories, Physics Department, Princeton University
*Received 1982 July 2; accepted 1982 August 13*



Davis, Efstathiou, Frenk & White 1985

THE ASTROPHYSICAL JOURNAL, 292:371–394, 1985 May 15
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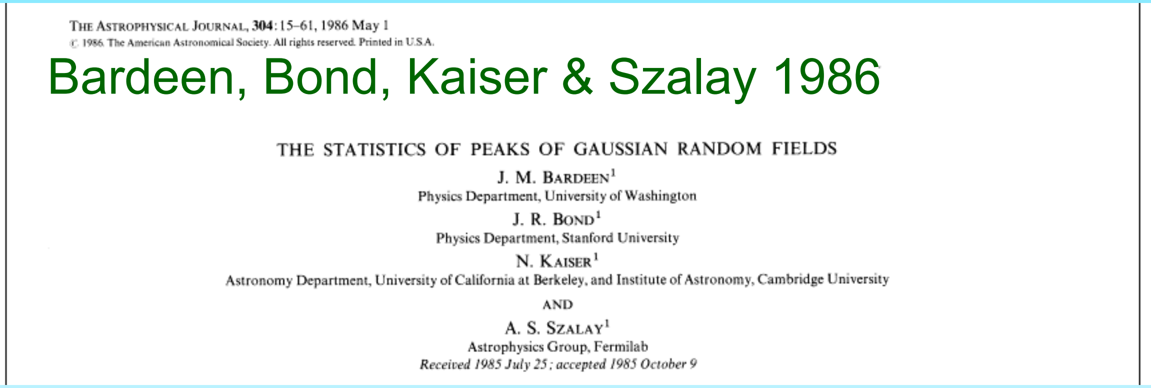
THE EVOLUTION OF LARGE-SCALE STRUCTURE IN A UNIVERSE DOMINATED BY COLD DARK MATTER

MARC DAVIS,[1,2] GEORGE EFSTATHIOU,[1,3] CARLOS S. FRENK,[1,4] AND SIMON D. M. WHITE[1,5]
*Received 1984 August 20; accepted 1984 November 30*



THE ASTROPHYSICAL JOURNAL, 304:15–61, 1986 May 1
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Bardeen, Bond, Kaiser & Szalay 1986

THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

J. M. BARDEEN[1]
Physics Department, University of Washington
J. R. BOND[1]
Physics Department, Stanford University
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AND
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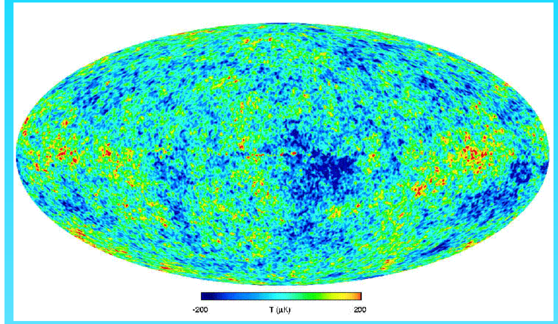
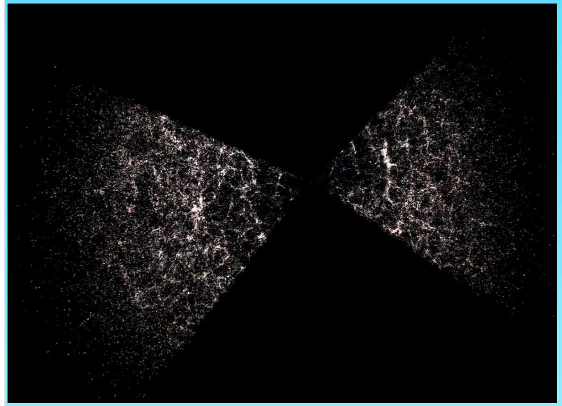
Astrophysics Group, Fermilab
*Received 1985 July 25; accepted 1985 October 9*

University of Durham

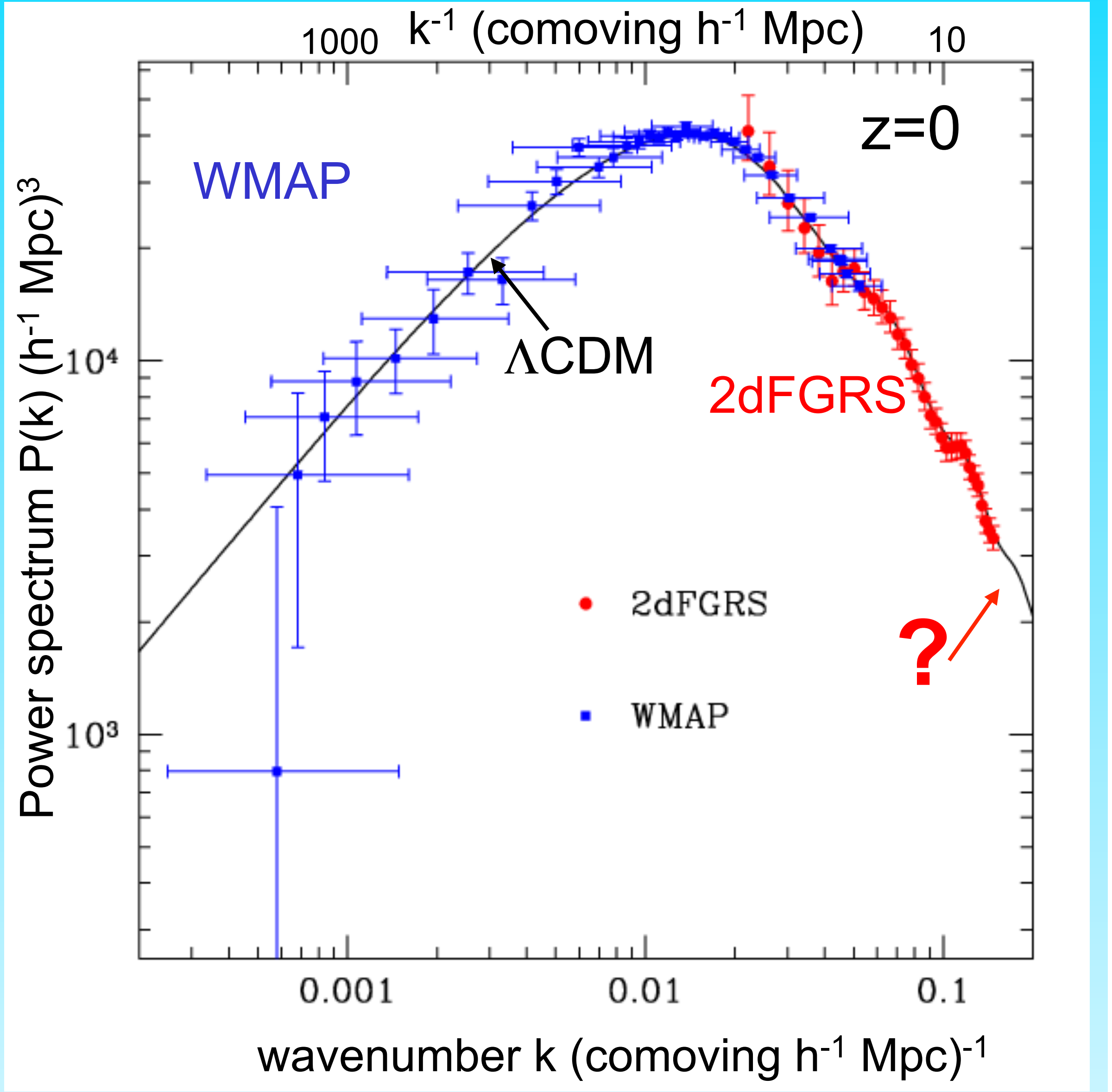
# The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0

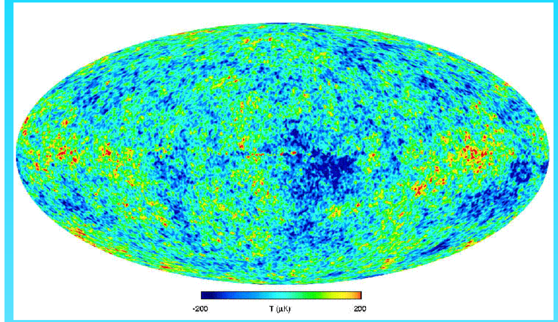


⇒ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

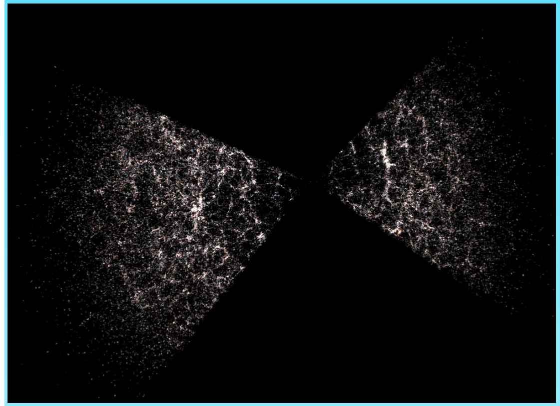
Sanchez et al 06

University of Durham

# The cosmic power spectrum: from the CMB to the 2dFGRS



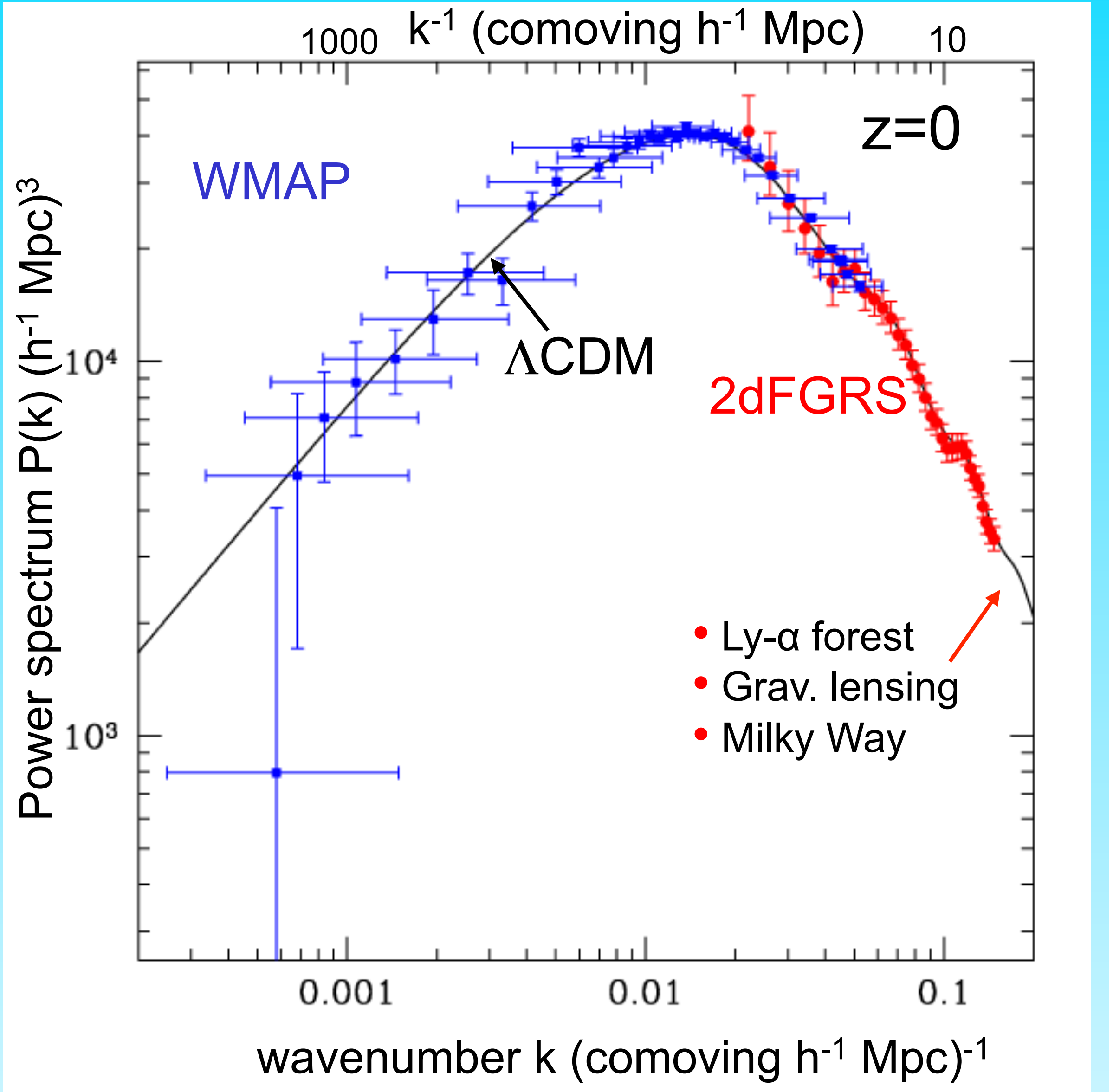
z~1000



z~0

$\Rightarrow$ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06



- Ly-α forest
- Grav. lensing
- Milky Way

The small-scale structure depends sensitively on the nature of the dark matter

# Non-baryonic dark matter candidates

| Type | example | mass |
|---|---|---|
| hot | neutrino | a few eV |
| warm | sterile $\nu$<br>majoron | keV-MeV |
| cold | axion<br>neutralino | $10^{-5}$eV-<br>>100 GeV |

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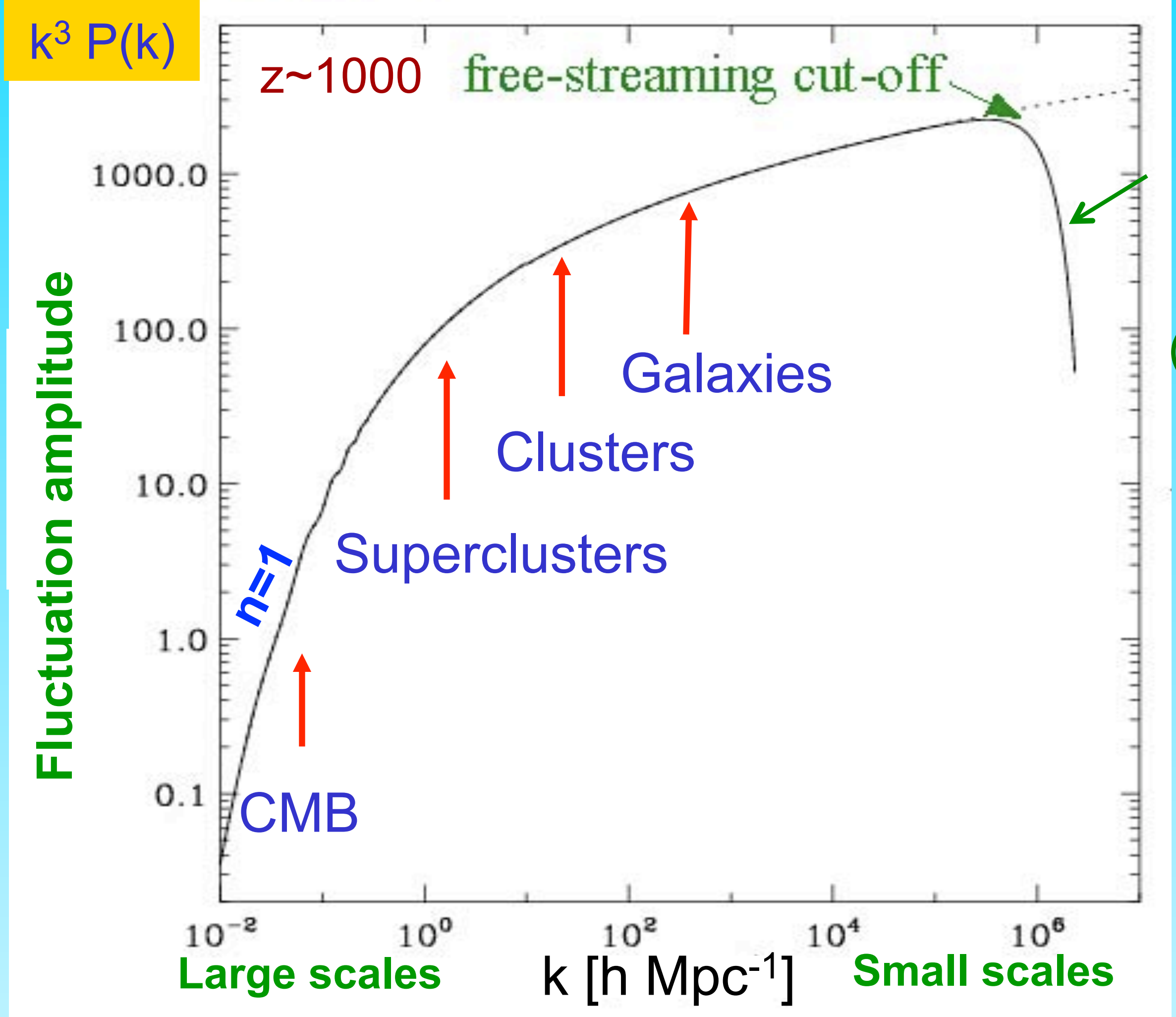
# The cold dark matter linear power spectrum

"Power per octave"



$10^{-6}$ $M_o$ for 100 GeV wimp (Green etal 04)

University of Durham

# The cold dark matter power spectrum

$\lambda_{cut} \propto m_x^{-1}$

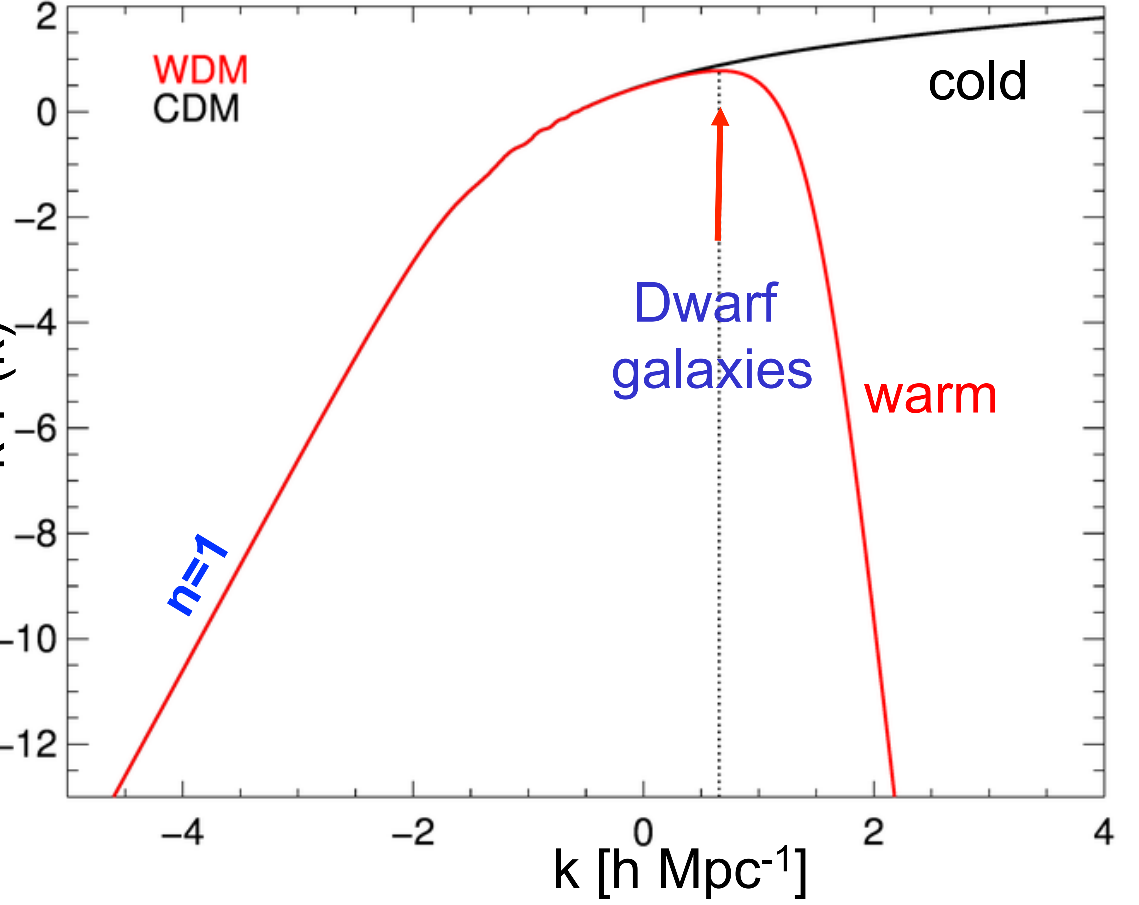
Ly-α forest (z~2-3) ➔

$m_{WDM} \gtrsim$ 4keV (2σ) for thermal relic

$m_{WDM} \gtrsim$ 2 keV (2σ) for sterile neutrinos

(Viel etal '08; Boyarsky etal '09)

The linear power spectrum ("power per octave" )



$M_{cut} \sim 10^{10} (\Omega /0.3)^{1.45} (h/0.65)^{3.9} (keV/m_{wdm})^{3.45}\ h^{-1}\ M_o$

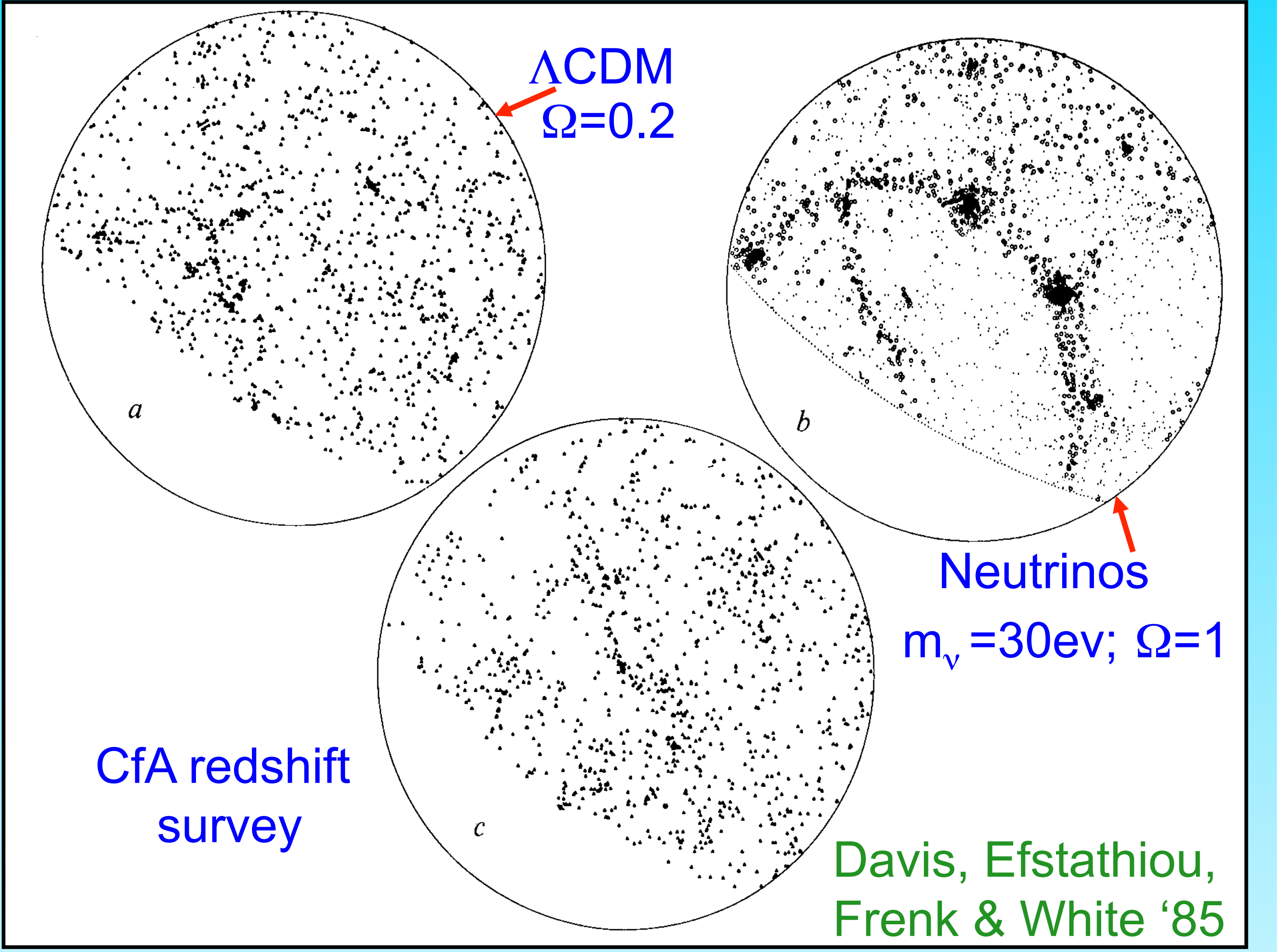
Institute for Computational Cosmology

# Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

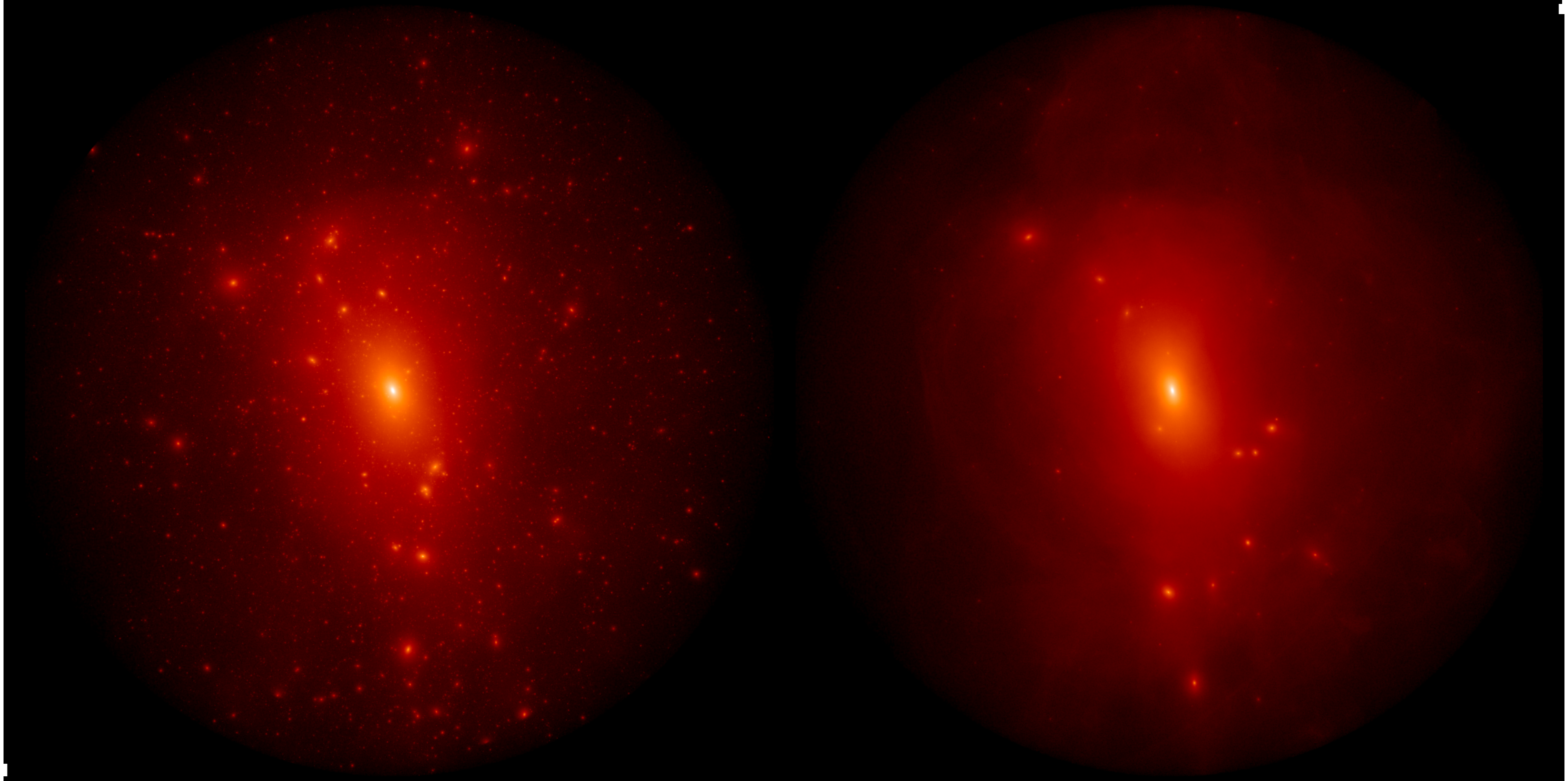
In CDM structure forms hierarchically



Davis, Efstathiou, Frenk & White ‘85

# Non-baryonic dark matter candidates

| Type | example | mass |
|---|---|---|
| ~~hot~~ | ~~neutrino~~ | ~~a few eV~~ |
| warm | sterile $\nu$<br>majoron | keV-MeV |
| cold | axion<br>neutralino | $10^{-5}$eV->100 GeV |



cold dark matter

warm dark matter

Gao, Lovell et al 2011

University of Durham

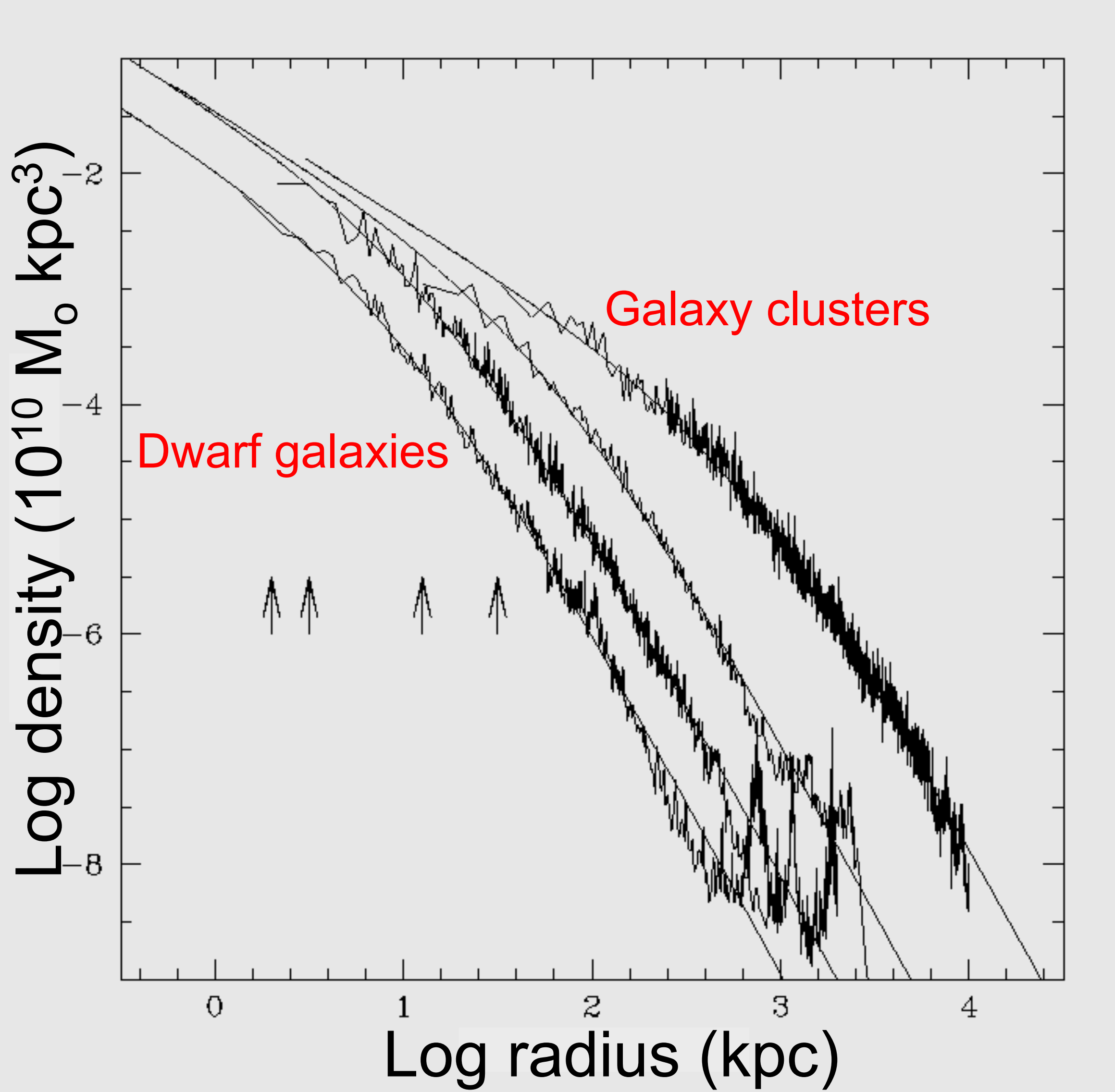
# The Milky Way and the nature of the dark matter

- Test CDM predictions on galaxy scales
  - Structure of dark matter halos
  - Number of satellite galaxies
  - Remnants of hierarchical formation (streams)


z = 48.4
T = 0.05 Gyr
500 kpc

# The structure of cold dark matter halos

# The Density Profile of Cold Dark Matter Halos



Halo density profiles are independent of halo mass & cosmological parameters

There is no obvious density plateau or `core' near the centre.

(Navarro, Frenk & White '97)

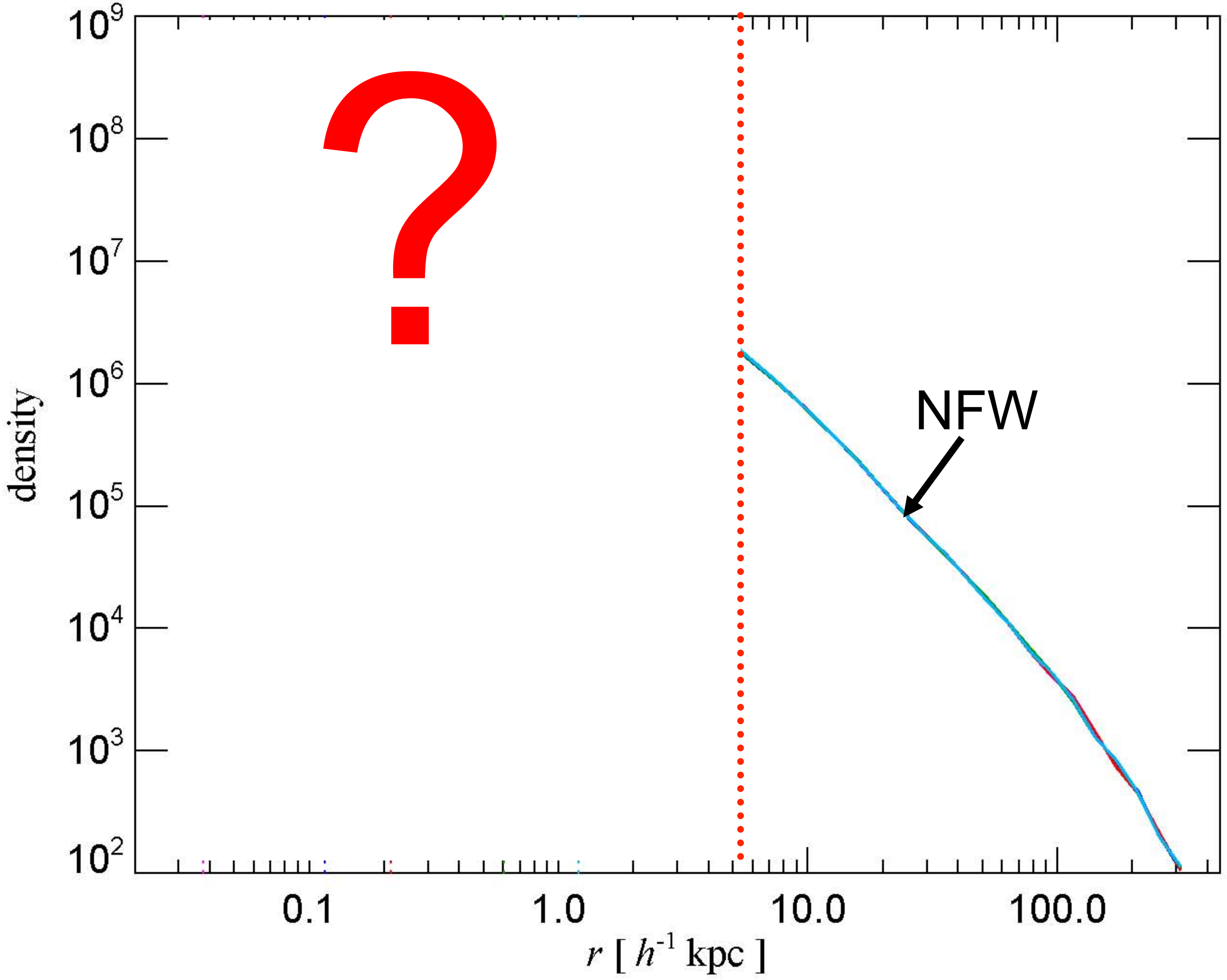
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

More massive halos and halos that form earlier have higher densities (bigger $\delta$)

University of Durham

# Density profile $\rho(r)$

Orignal NFW simulations resolved down to 5% of $r_{vir}$



# The structure of cold dark matter halos

## Dark matter density profile: the central cusp ?

# The Aquarius programme

Carlos Frenk

Amina Helmi

Adrian Jenkins

Aaron Ludlow

Julio Navarro

Volker Springel,

Mark Vogelsberger

Jie Wang

Simon White

Aquarius ++

Shaun Cole

Andrew Cooper

Gabriella de Lucia

Takashi Okamoto

UK, Germany, Netherlands, Canada, Japan, China collaboration

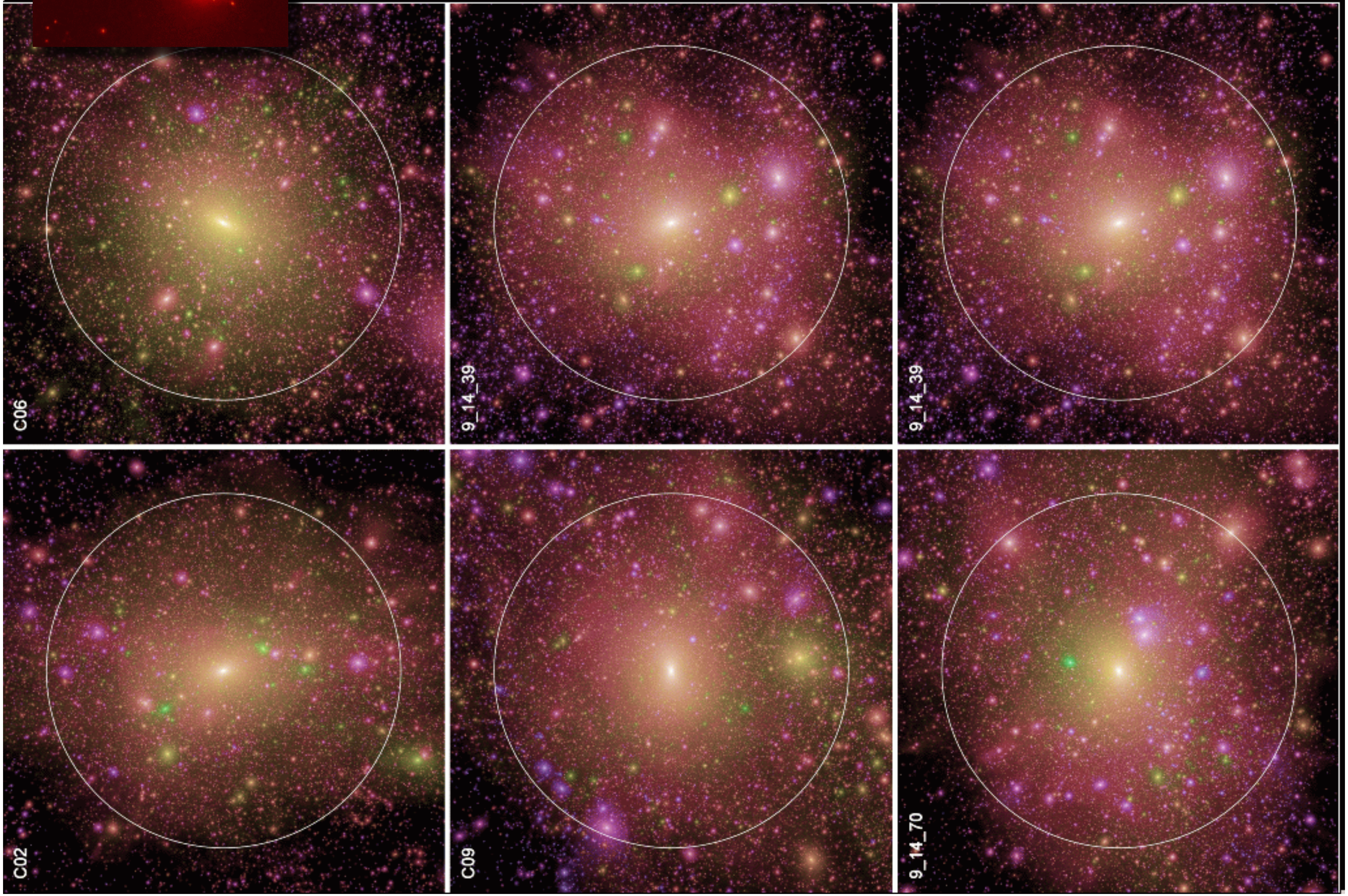
**Pictures, movies and simulation data**

**available at:**

**http://www.mpa-garching.mpg.de/Virgo**

**www.durham.ac.uk/virgo**

# Images of all Aquarius halos (level-2)



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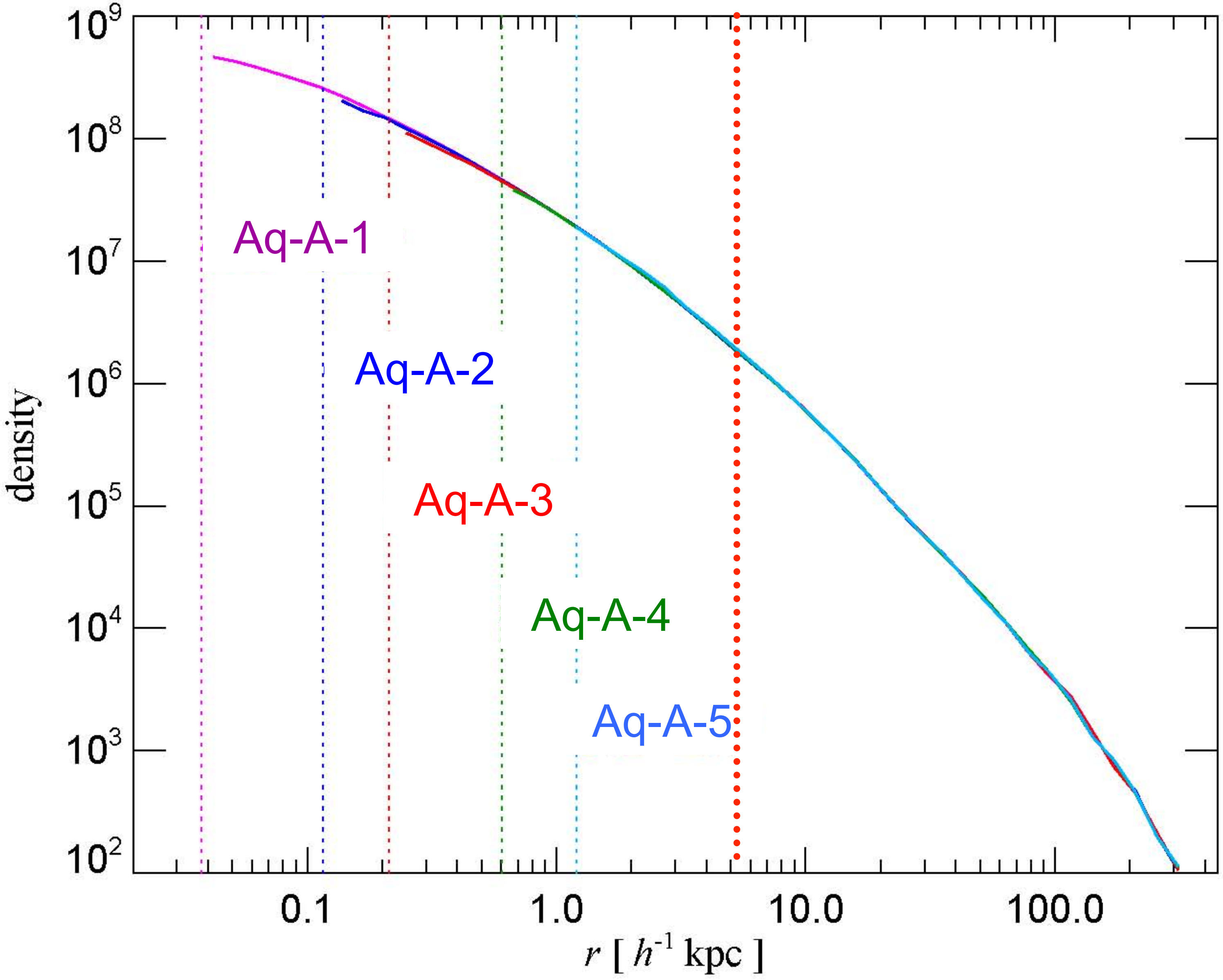
# Density profile ρ(r)



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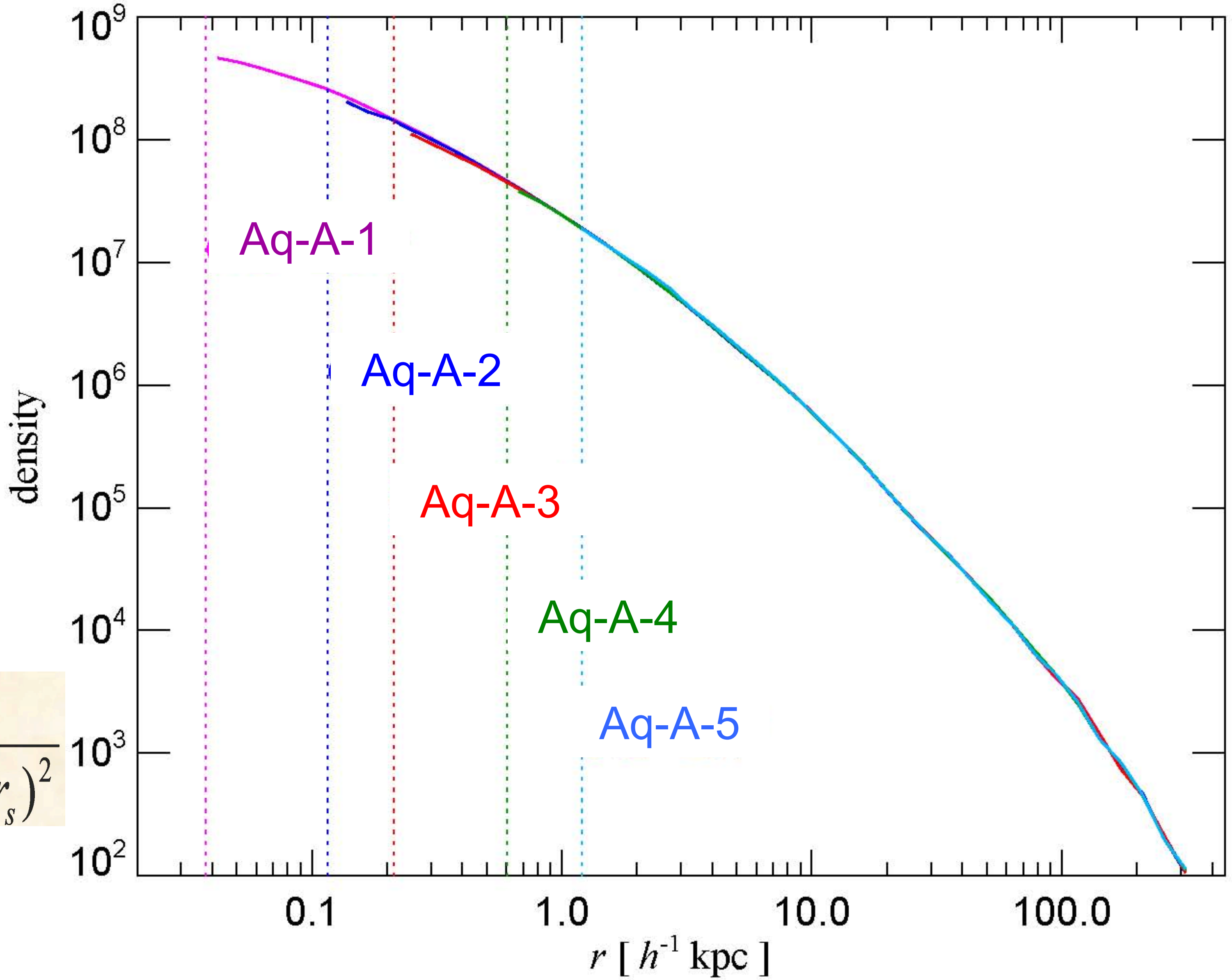
# Density profile ρ(r): convergence test

The spherically averaged density profiles show very good convergence, and are approximately fit by a NFW profile

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$



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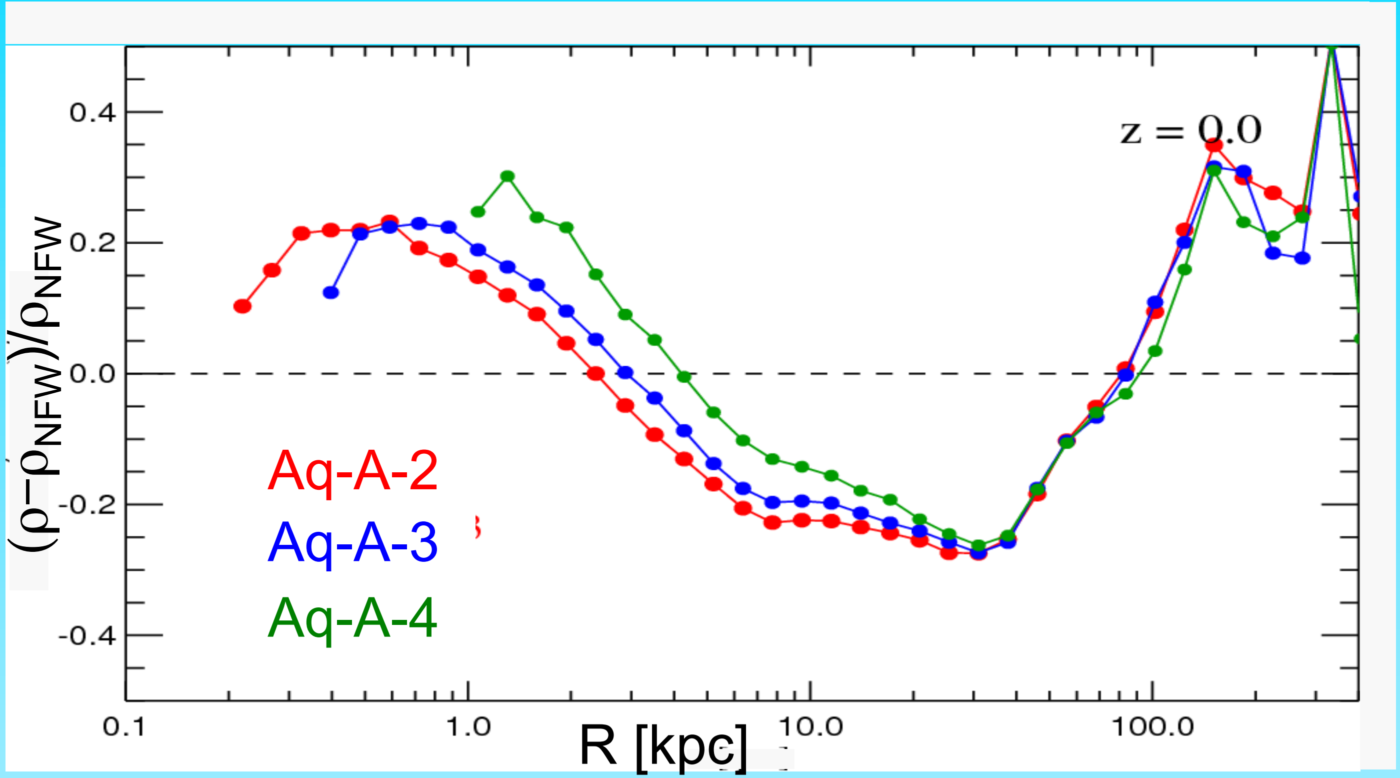
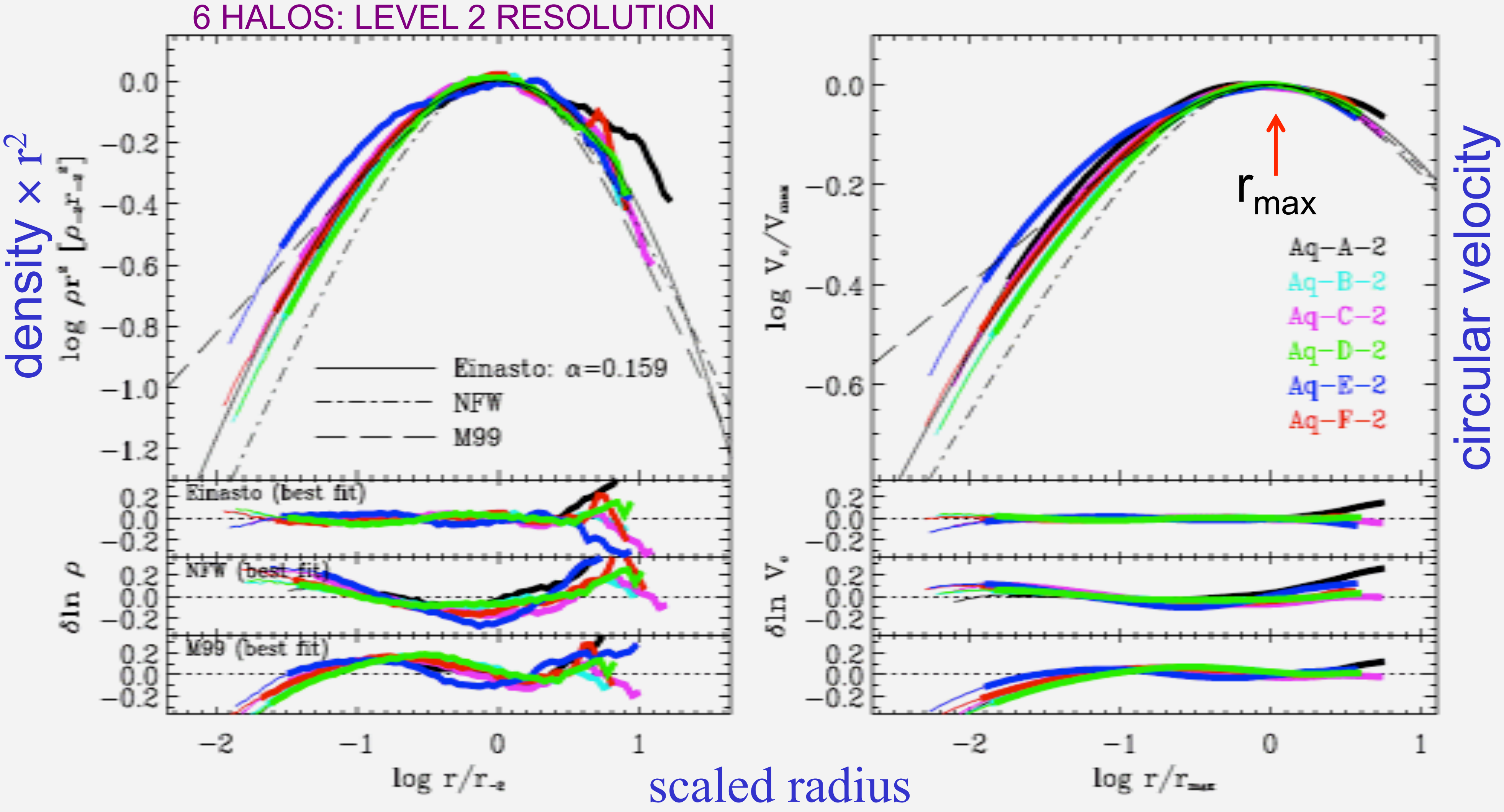
# Deviations from NFW



The density profile is fit by the NFW form to ~10-20%.
In detail, the shape of the profile is slightly different.

# Universality of the mass profile

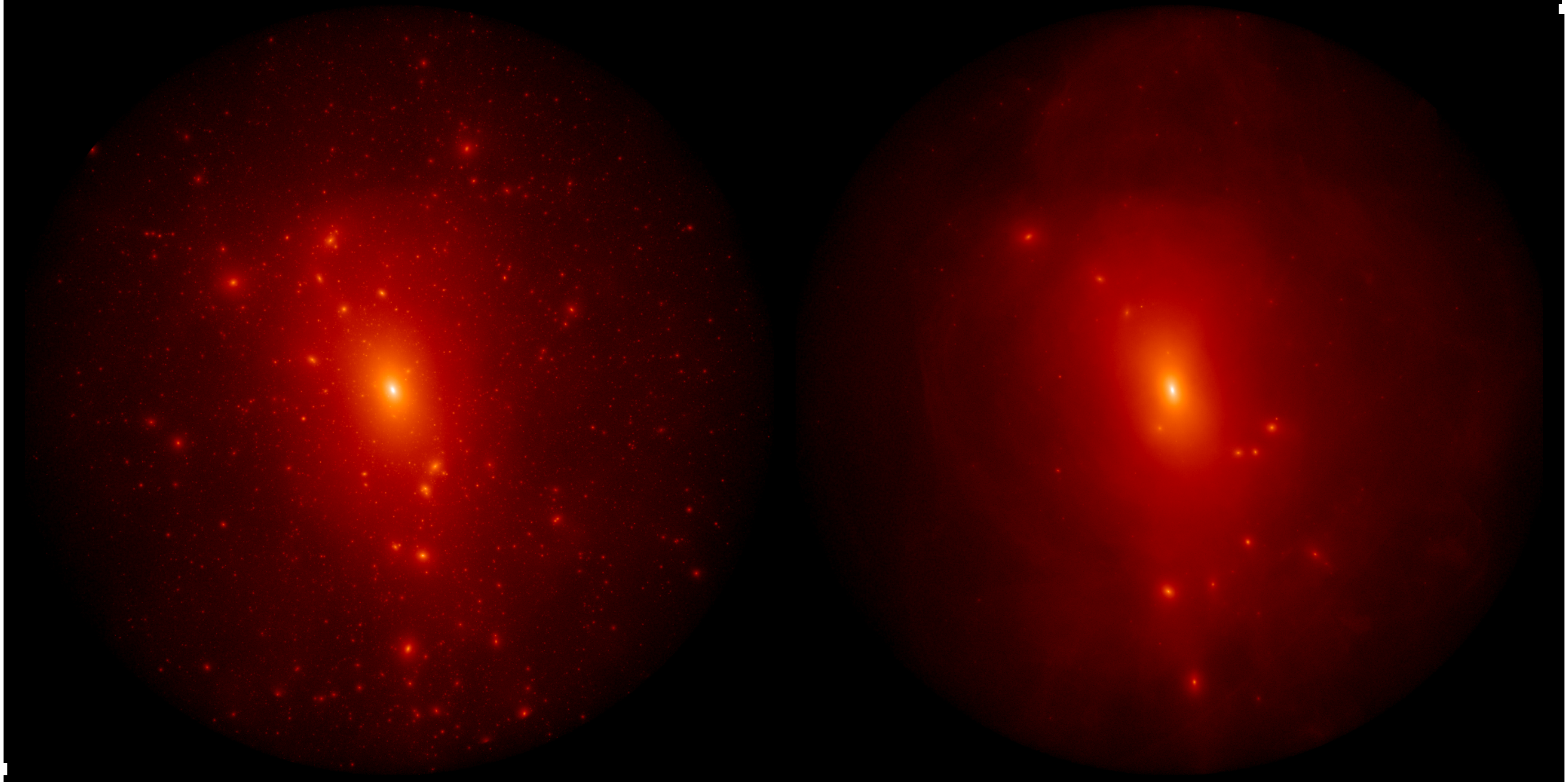
6 HALOS: LEVEL 2 RESOLUTION



Slight but significant deviations from similarity.

A “third parameter” needed to describe accurately mass profiles of CDM halos.

Einasto: $\ln(\rho/\rho_{-2}) = -(2/\alpha)[(r/r_{-2})^{\alpha} - 1].$ Virgo Consortium 08



cold dark matter

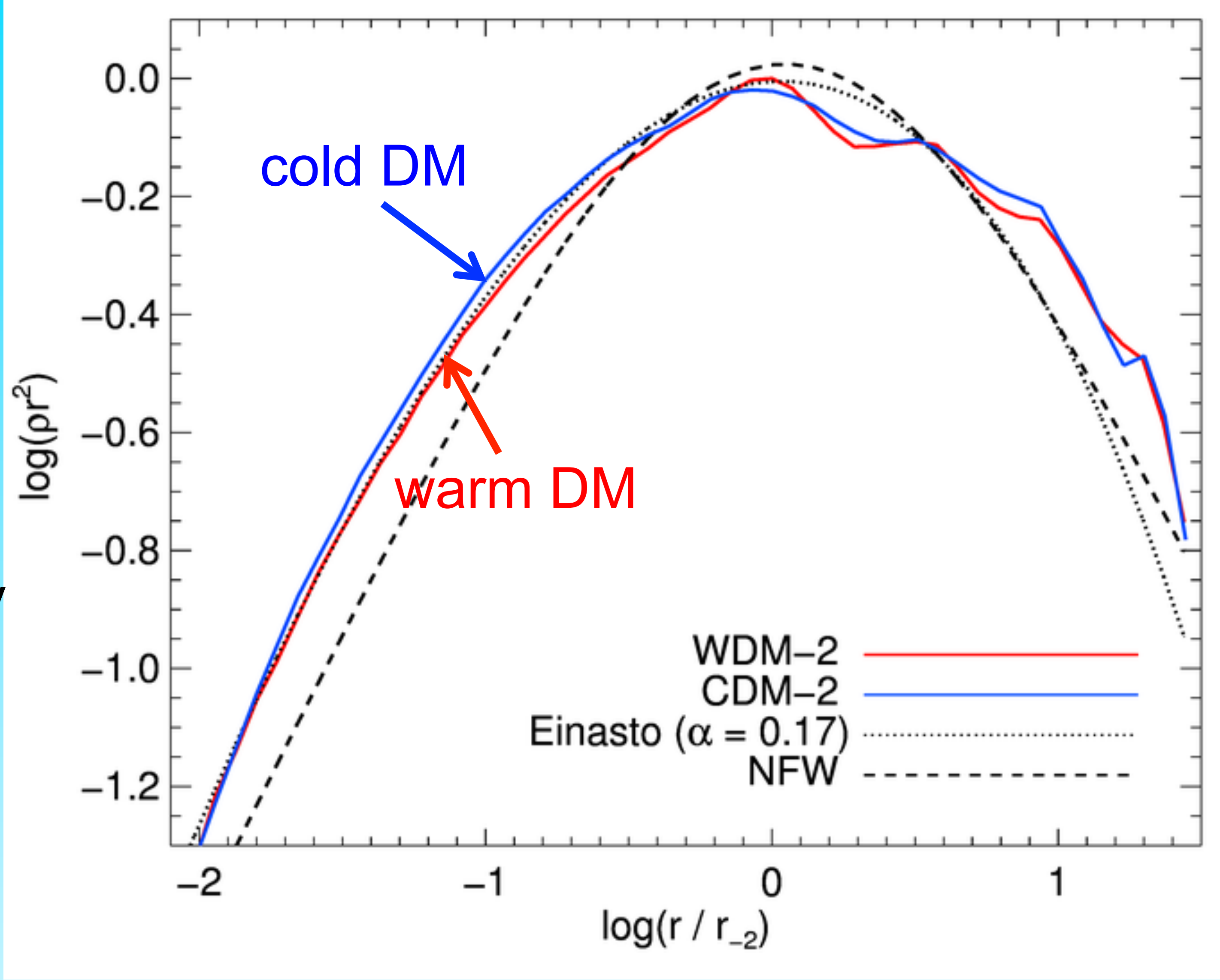
warm dark matter

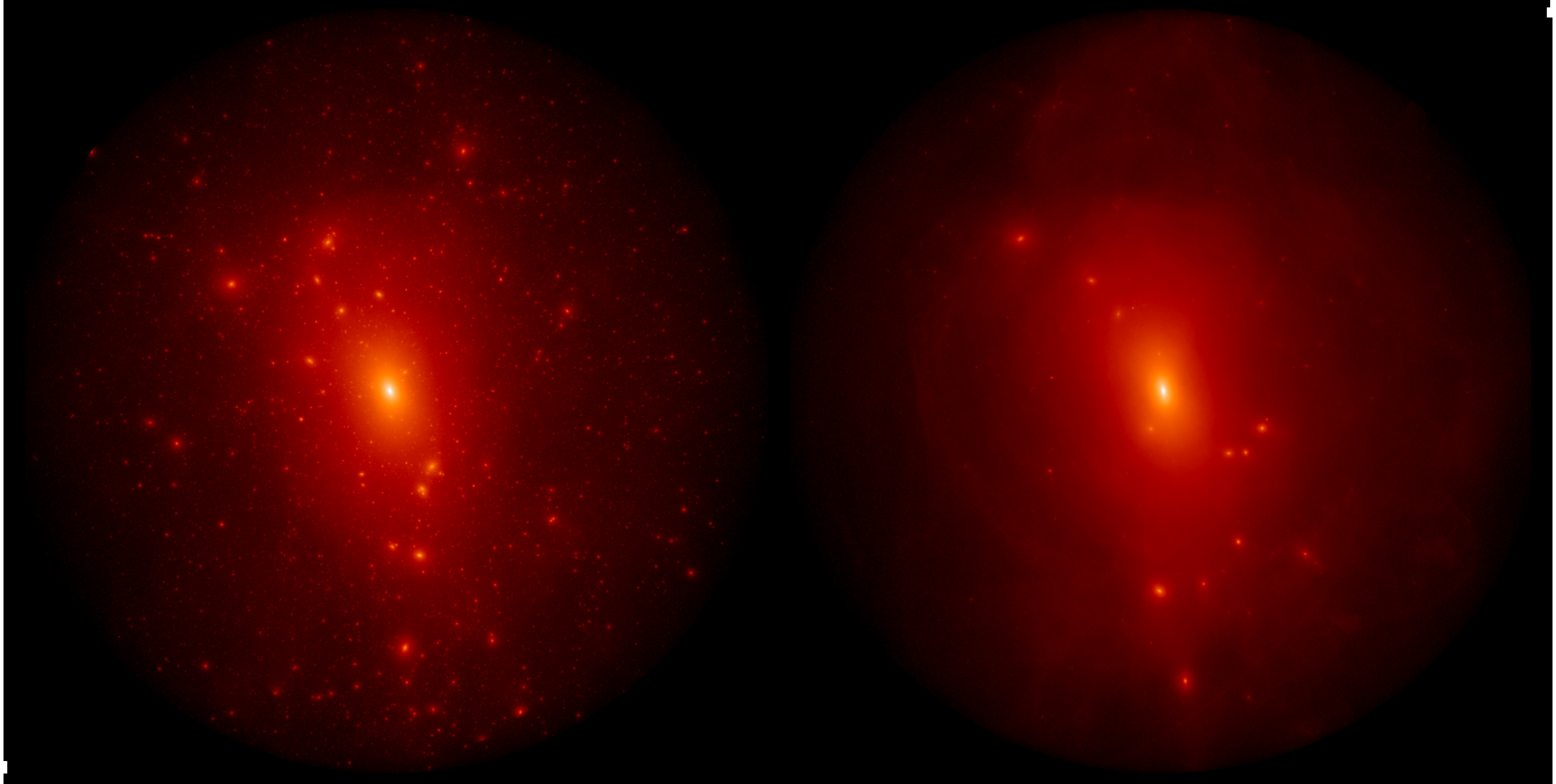
Gao, Lovell et al 2011

# Density profile $\rho(r)$

Central cusp also exists in WDM…

but, depending on the particle mass, substructures may have cores, not cusps





cold dark matter

warm dark matter

Gao, Lovell et al 2011

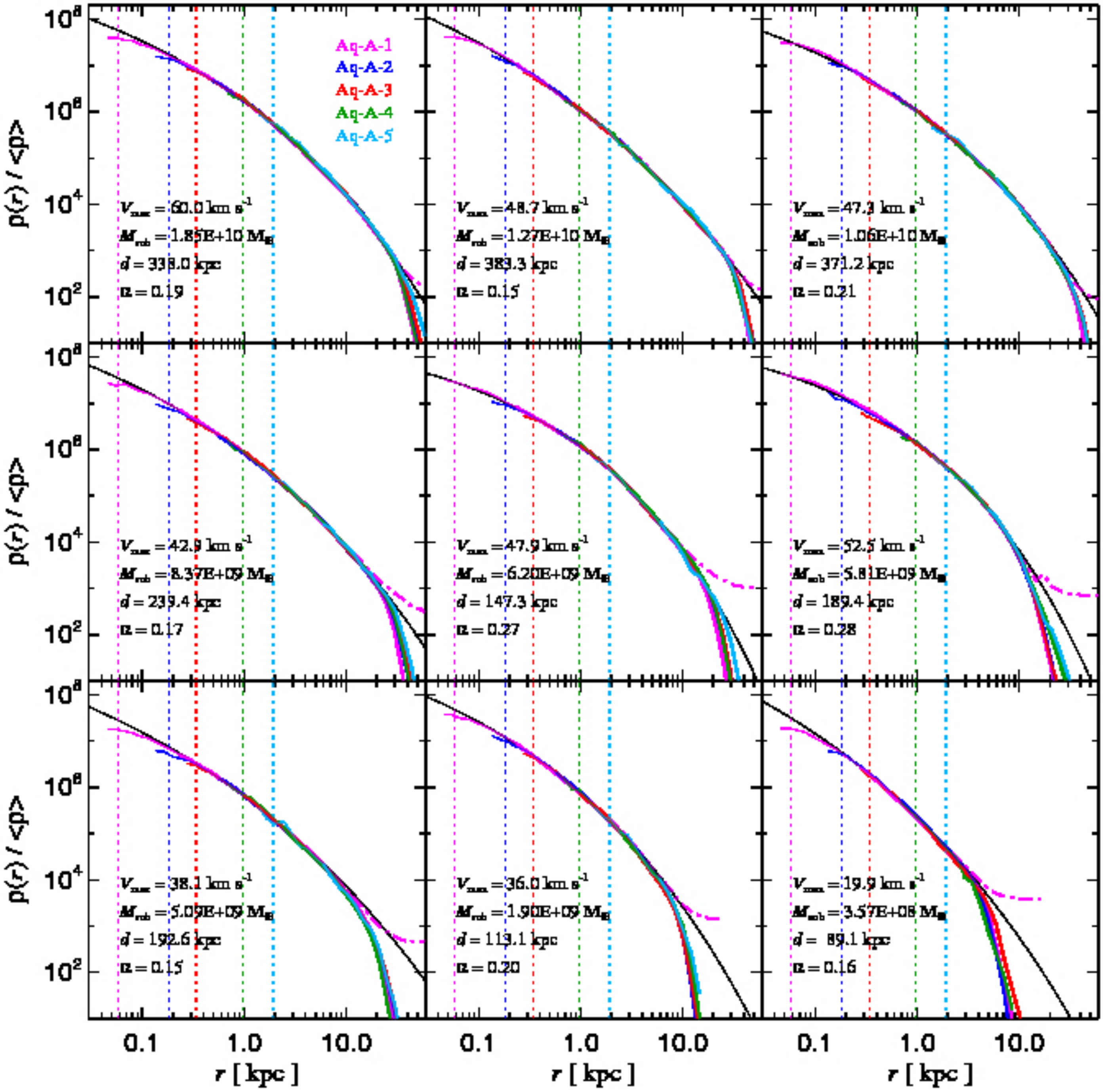
University of Durham

# Subhalo density profiles

Well fit by Einasto

converged to r=100pc

Springel et al’08



# A cold dark matter universe

N-body simulations show that cold dark matter halos (from galaxies to clusters) have:

"Cuspy" density profiles ← fundamental prediction of CDM

Does nature have them?

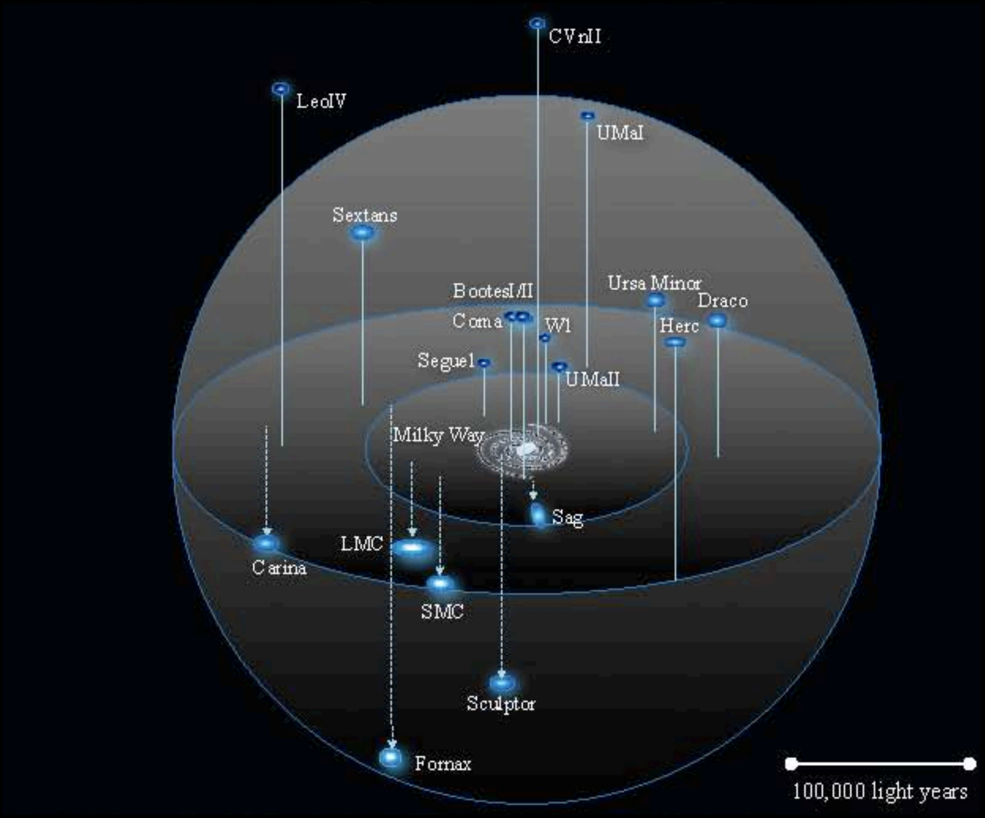
Look in galaxies and clusters

Halo could be modified by the galaxy forming in it ?

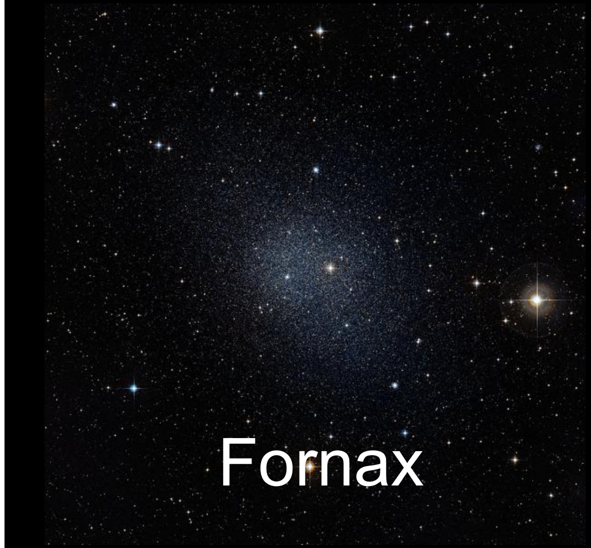
Best place to look: dwarf satellites of the MW

Dw Sph have (M/L)~1000 ➔ baryon effects not important ?

# The satellites of the Milky Way”



# Dwarf galaxies around the Milky Way


Fornax


Sculptor


Leo I

© Anglo-Australian Observatory


Sextans


Carina


Sagittarius

University of Durham

# The structure of dark matter halos

## Dwarf sphs: cores or cusps?

Jeans eqn:

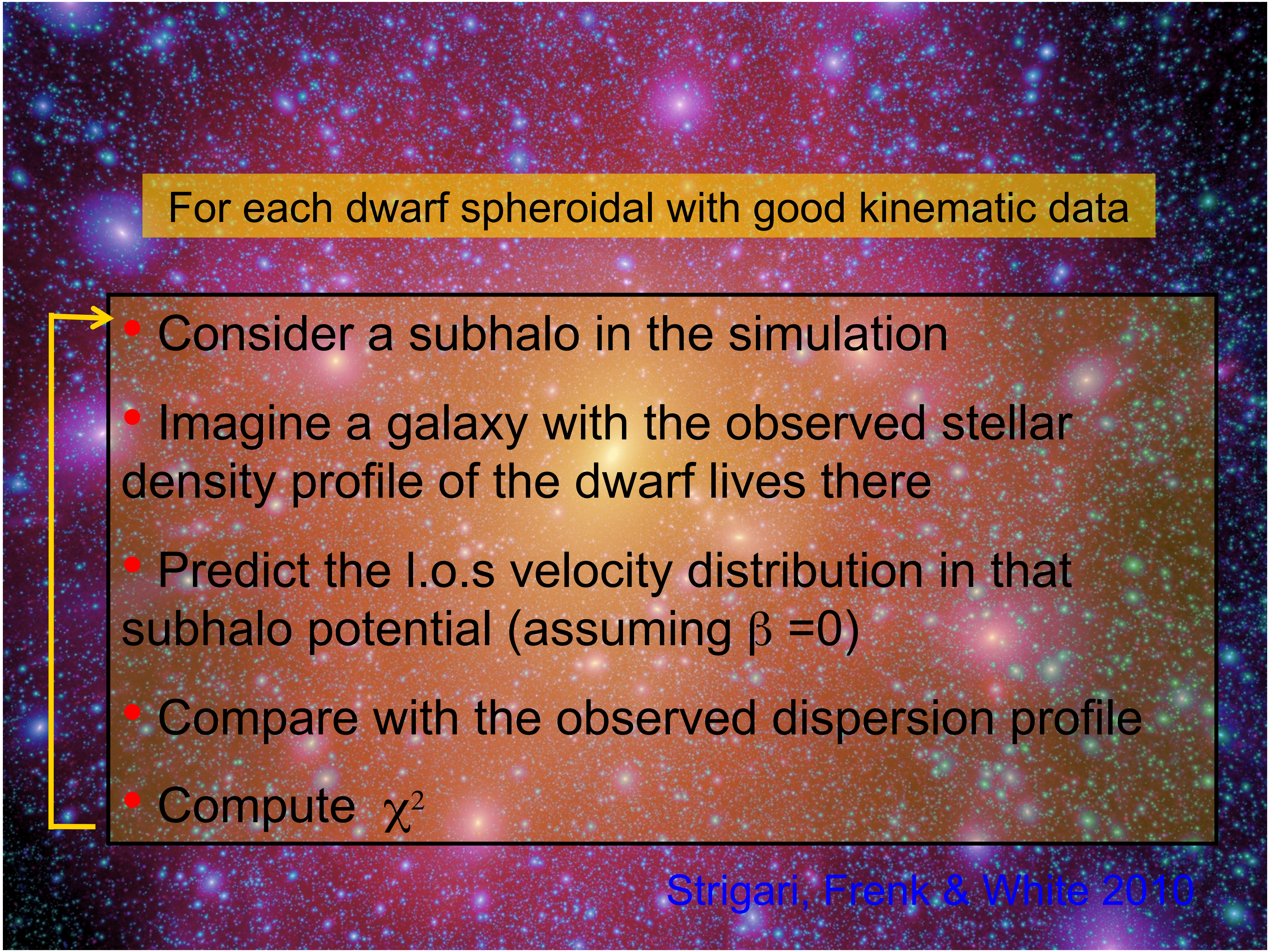
stellar density profile

radial velocity dispersion

$$\frac{GM(r)}{r} = -\sigma_r^2\left[\frac{d\ln\rho_*}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

from Aquarius sim

vel. anisotropy



For each dwarf spheroidal with good kinematic data

- Consider a subhalo in the simulation
- Imagine a galaxy with the observed stellar density profile of the dwarf lives there
- Predict the l.o.s velocity distribution in that subhalo potential (assuming $\beta = 0$)
- Compare with the observed dispersion profile
- Compute $\chi^2$

Strigari, Frenk & White 2010

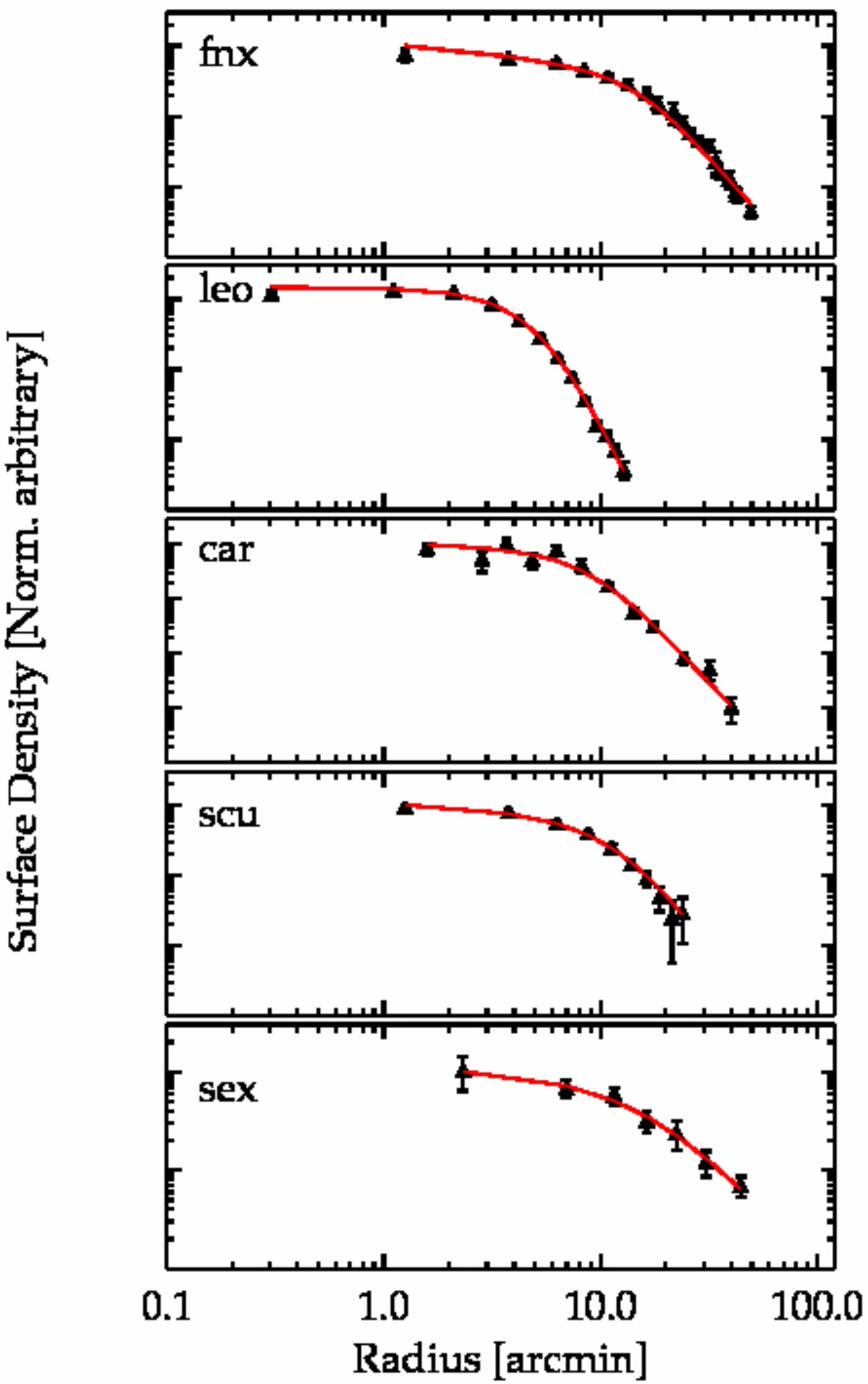
University of Durham

# Milky Way Dwarfs

Fit stellar surface density profile with a 3D profile of the form:

$$\rho_*(r) \propto \frac{1}{x^a(1+x^b)^{(c-a)/b}}$$

| Satellite | a | $\chi^2$ /d.o.f. |
|---|---|---|
| Fornax | 1 | 1.0 |
| Leo I | 0 | 1.6 |
| Carina | 0.5 | 1.1 |
| Sculptor | 0.5 | 0.4 |
| Sextans | 0.5 | 01 |



Strigari, Frenk & White 2010

University of Durham

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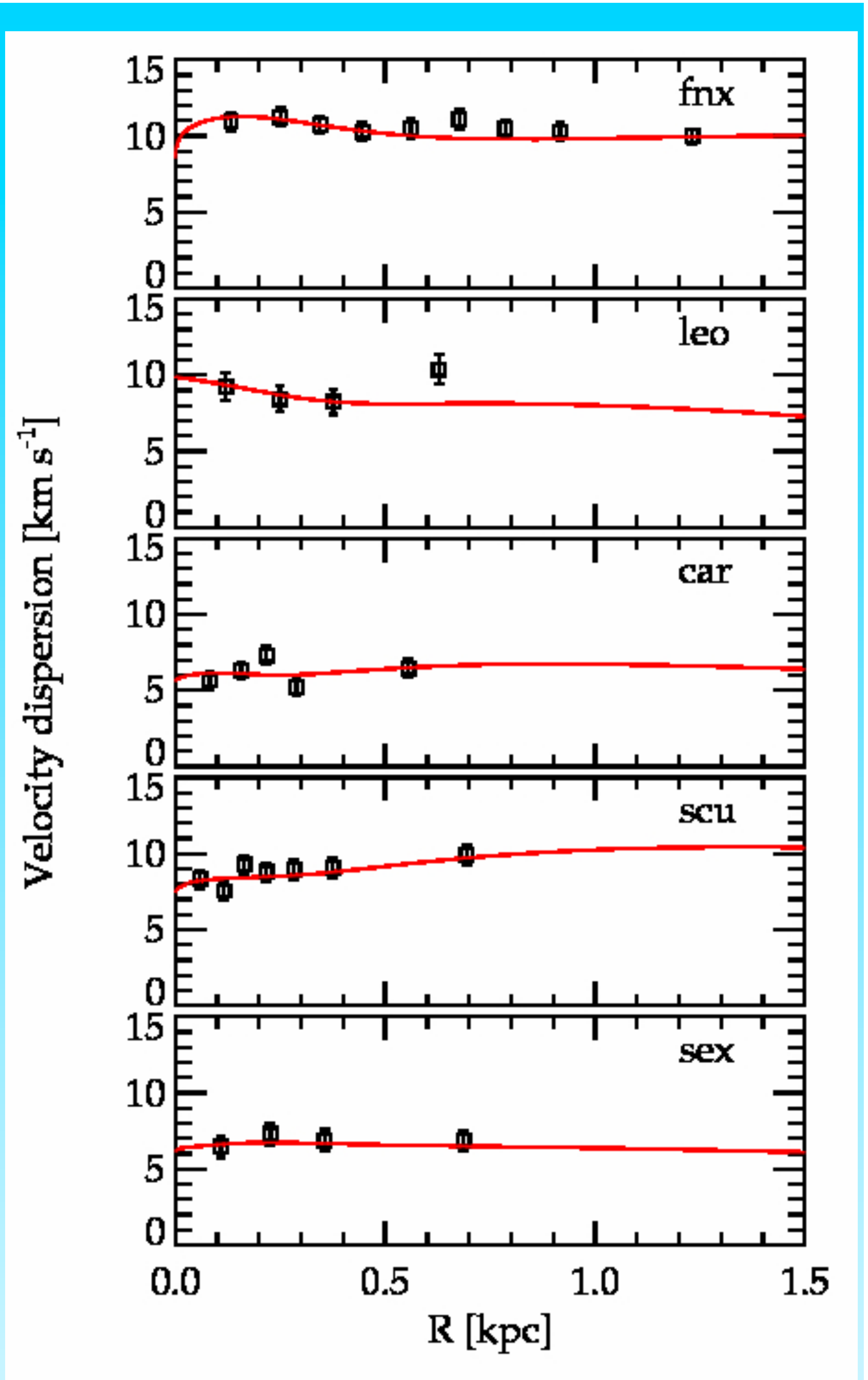
from Aquarius sim

vel. anisotropy

- Assume isotropic orbits
- Solve for $\sigma_r$ (r)
- Compare with observed $\sigma_r$ (r)
- Find “best fit” subhalo



ICC
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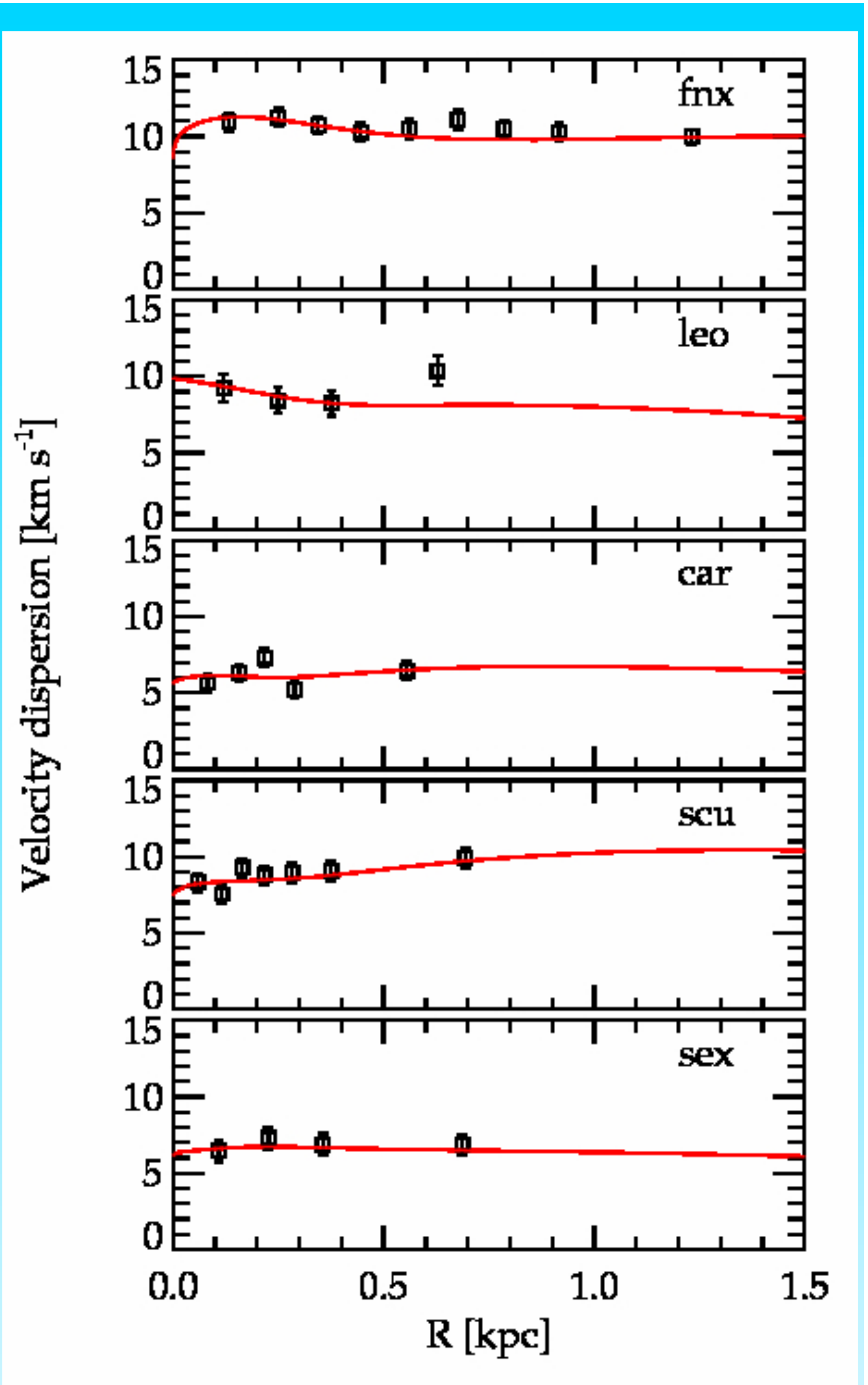
$$\frac{GM(r)}{r} = -\sigma_r^2\left[\frac{d\ln\rho_*}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

from Aquarius sim

vel. anisotropy

1-p= prob. that “best fit” can be rejected (β=0)

| **Satellite** | **1-p** |
|---|---|
| Fornax | 0.4 |
| Leo I | 0.5 |
| Carina | 0.4 |
| Sculptor | 0.8 |
| Sextans | 0.2 |



Strigari, Frenk & White 2010

University of Durham

# Velocity distribution function

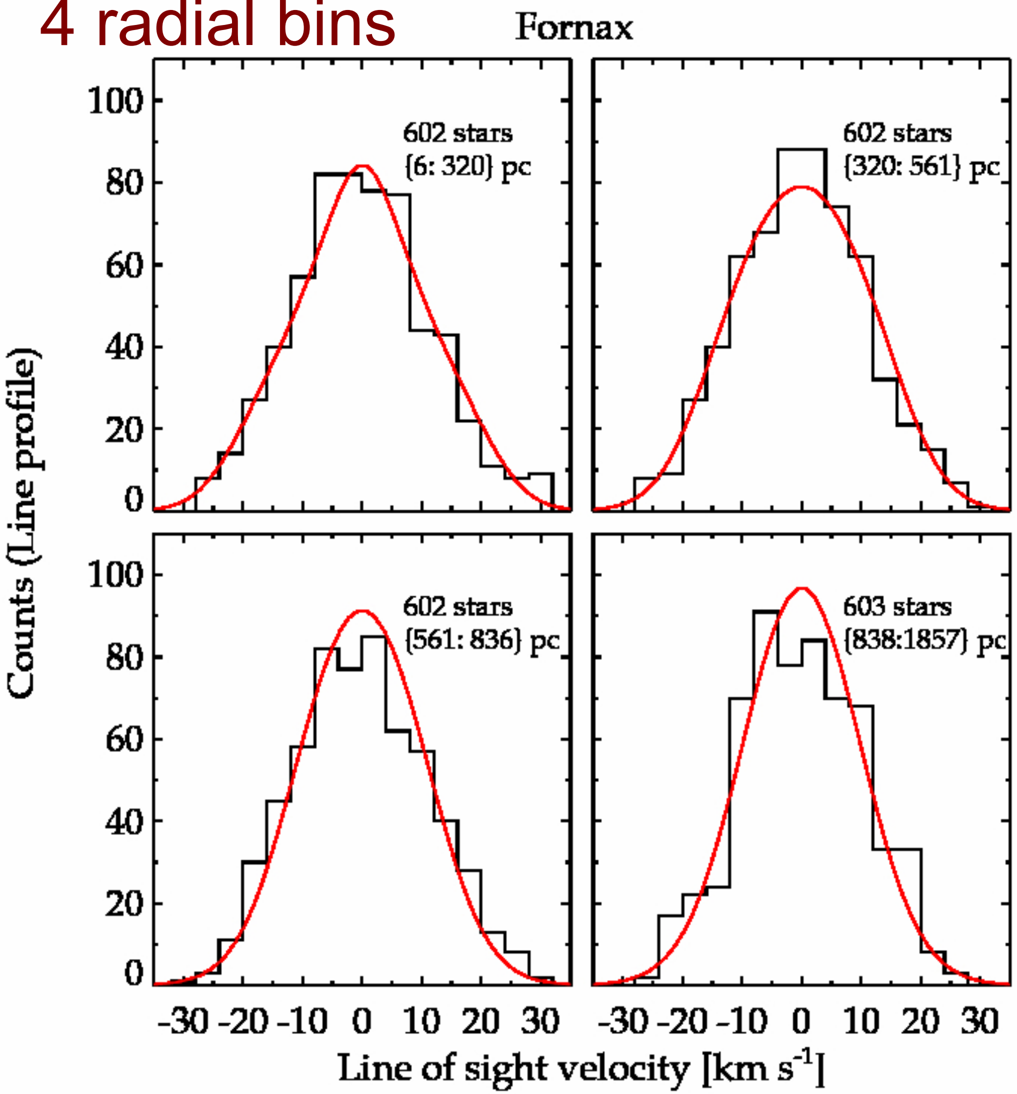
$$f(\varepsilon) = \frac{1}{\sqrt{8}\pi^2} \int_\varepsilon^0 \frac{d^2\rho_*}{d\Psi^2} \frac{d\Psi}{\sqrt{\Psi - \varepsilon}}$$

$$\varepsilon = \Psi(r) + v^2/2$$

KS rejection  probability (β=0)

| **Satellite** | **b1** | **b2** | **b3** | **b4** |
|---|---|---|---|---|
| Fornax | 0.95 | 0.85 | .997 | 0.98 |
| Leo I | 0.54 | 0.48 | 0.69 | .997 |
| Carina | 0.49 | 0.56 | 0.71 | 0.66 |
| Sculptor | 0.68 | 0.32 | 0.38 | 0.33 |
| Sextans | 0.59 | 0.19 | 0.97 | 0.03 |

4 radial bins



Strigari, Frenk & White 2010

University of Durham

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Strigari, Frenk & White 2010

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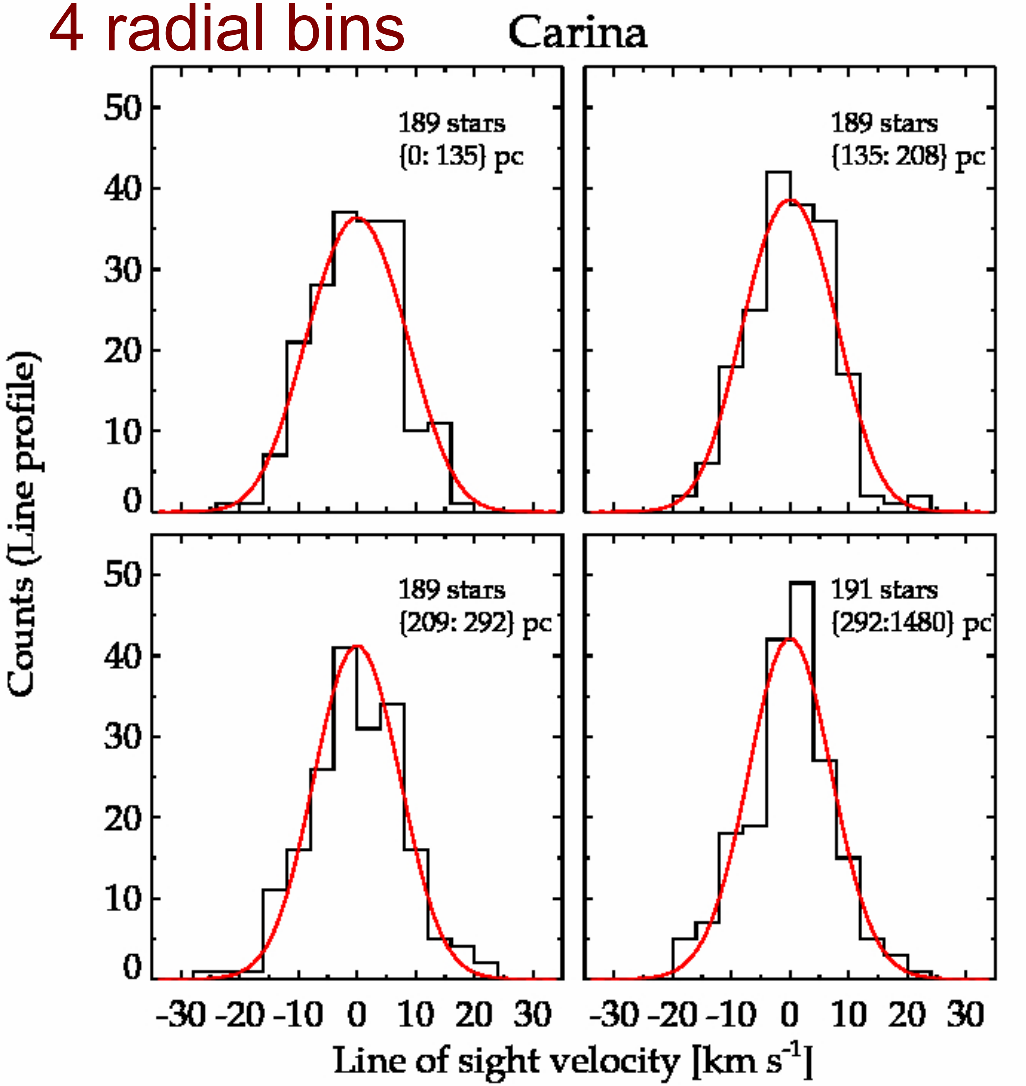

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| Satellite | b1 | b2 | b3 | b4 |
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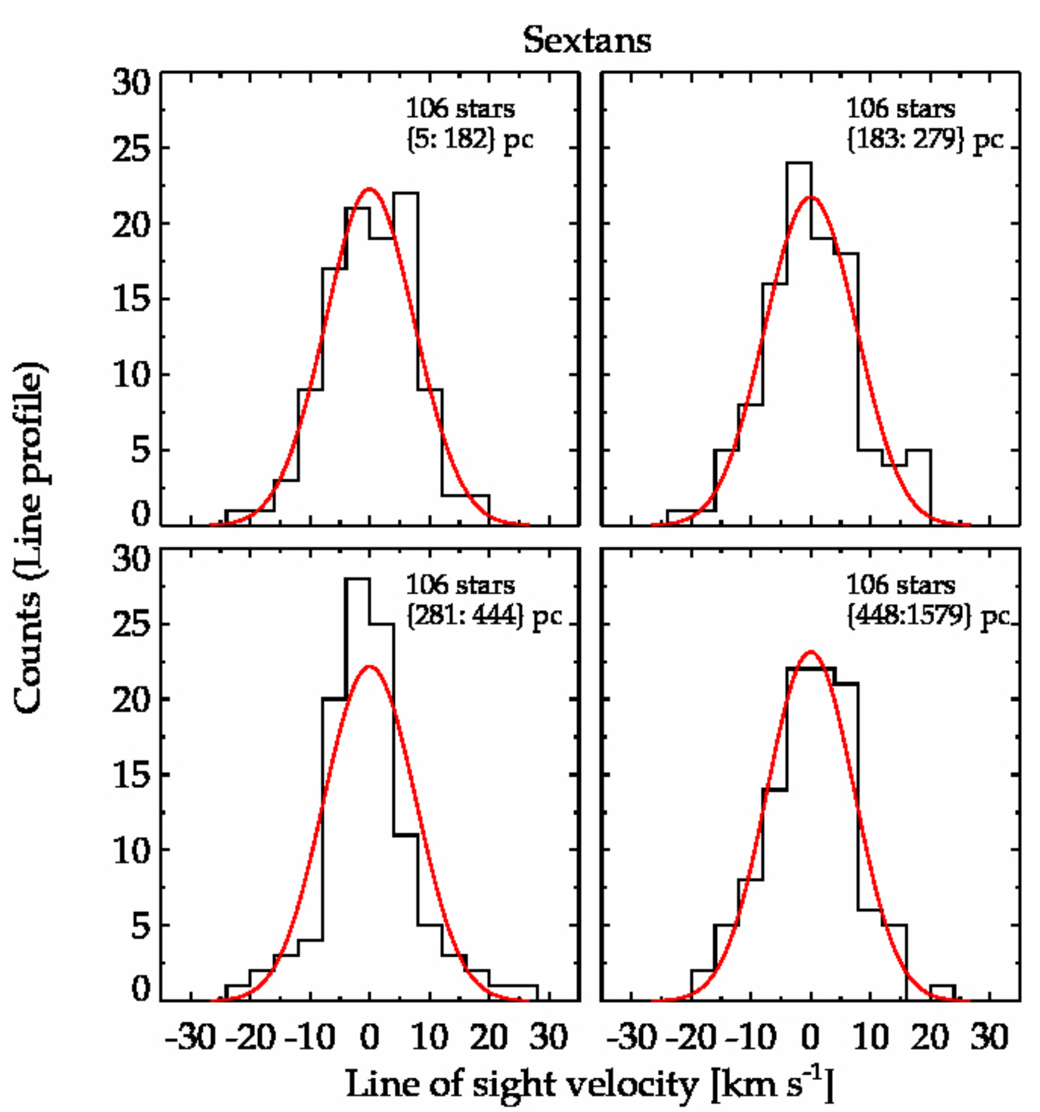


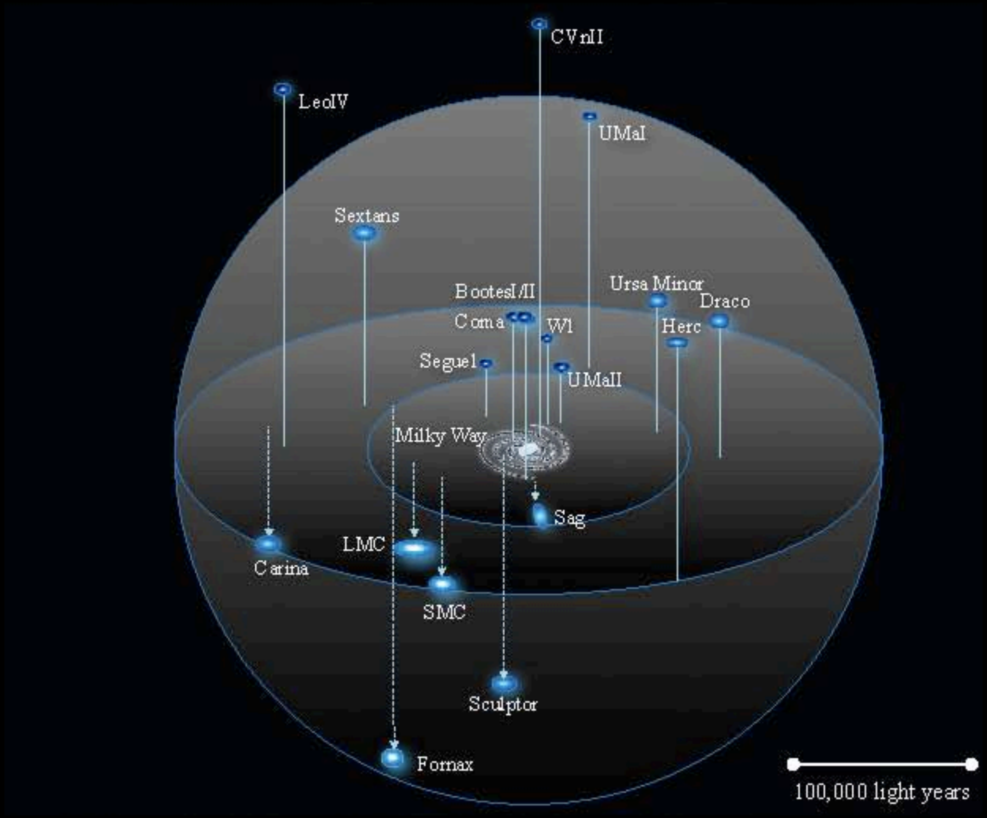
Strigari, Frenk & White 2010

# The structure of cold dark matter halos

Photometric and kinematic data for Milky Way satellites (Fornax, Carina, Leo I, Sculptor and Sextans) consistent with cuspy NFW profiles

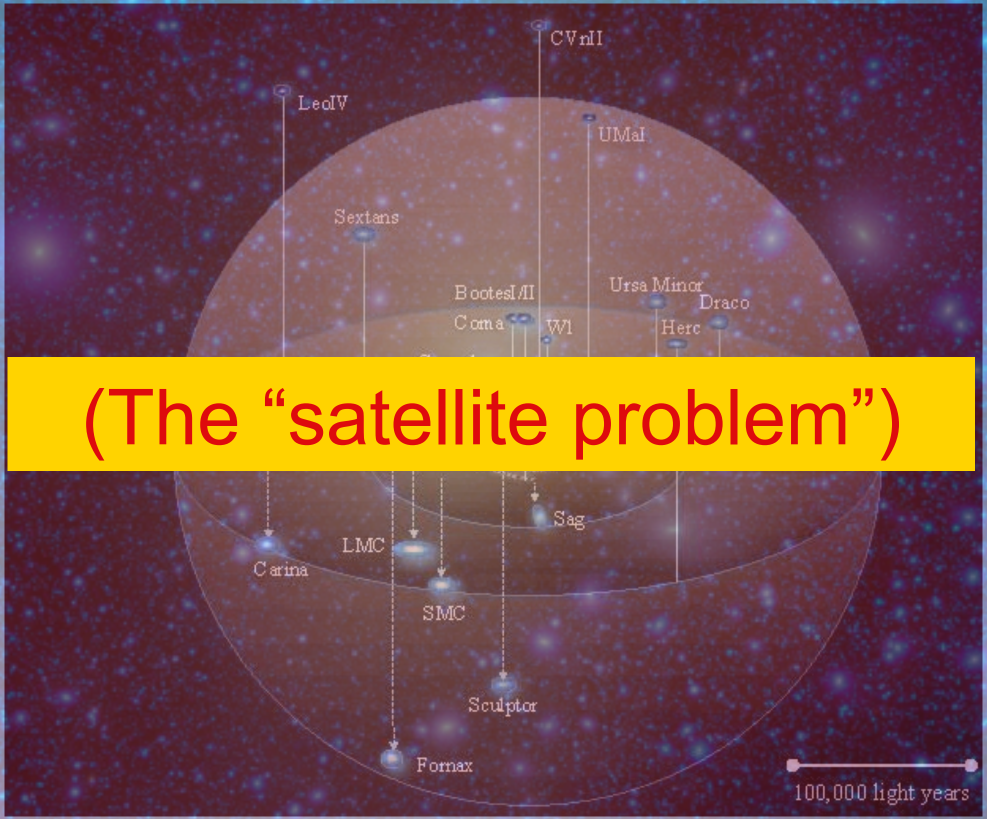
Strong conclusion because MW satellites have large M/L (~1000) and thus the reveal original structure of their dark matter halos

# Does CDM predict the right number of satellites?



# Simulations produce $>10^5$ subhalos

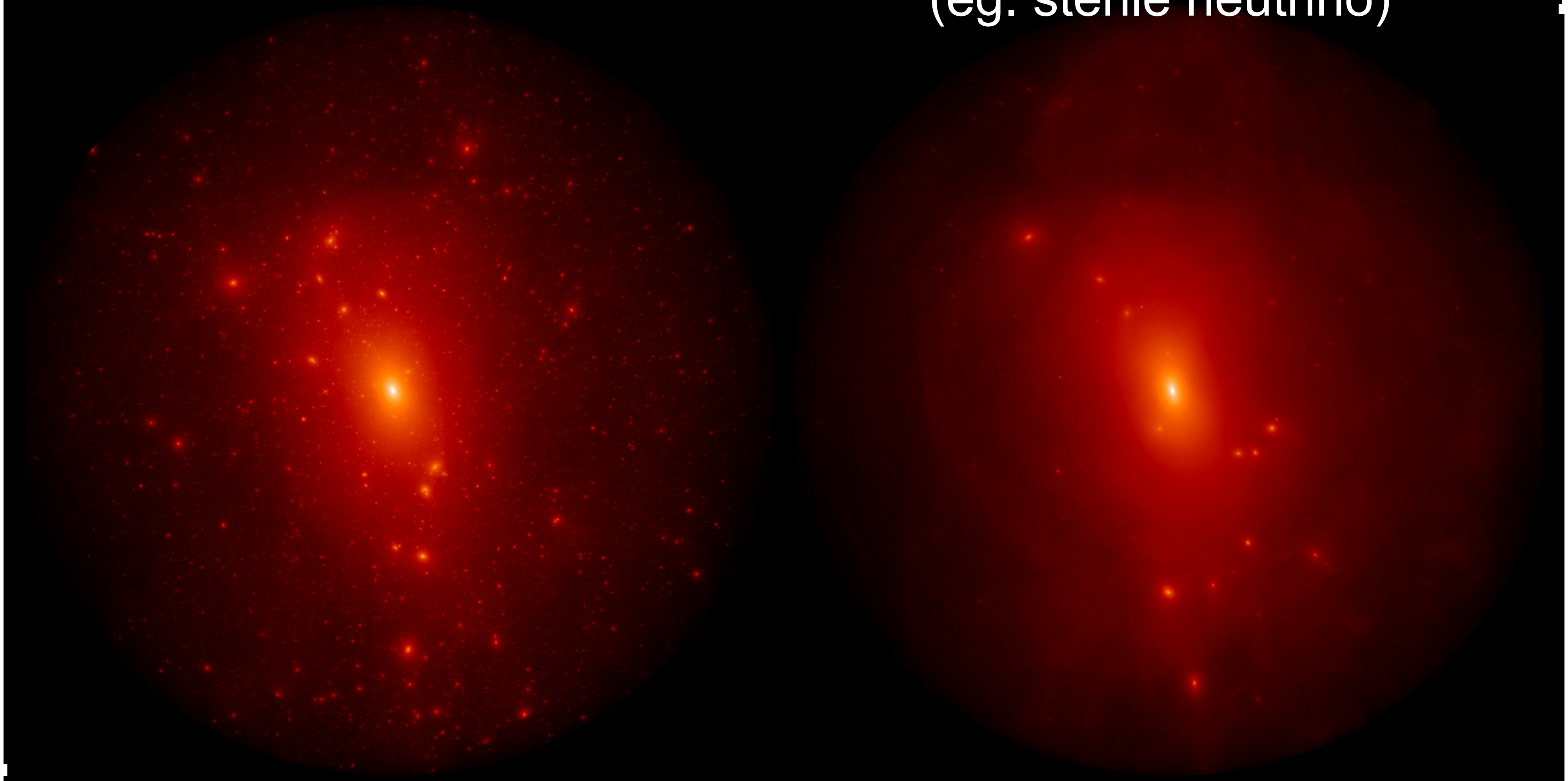
# Simulations produce >$10^5$ subhalos



(The “satellite problem”)

But only a few tens of satellites have been discovered in the Milky Way cold dark matter

warm dark matter
(eg. sterile neutrino)



Gao, Lovell et al 2011

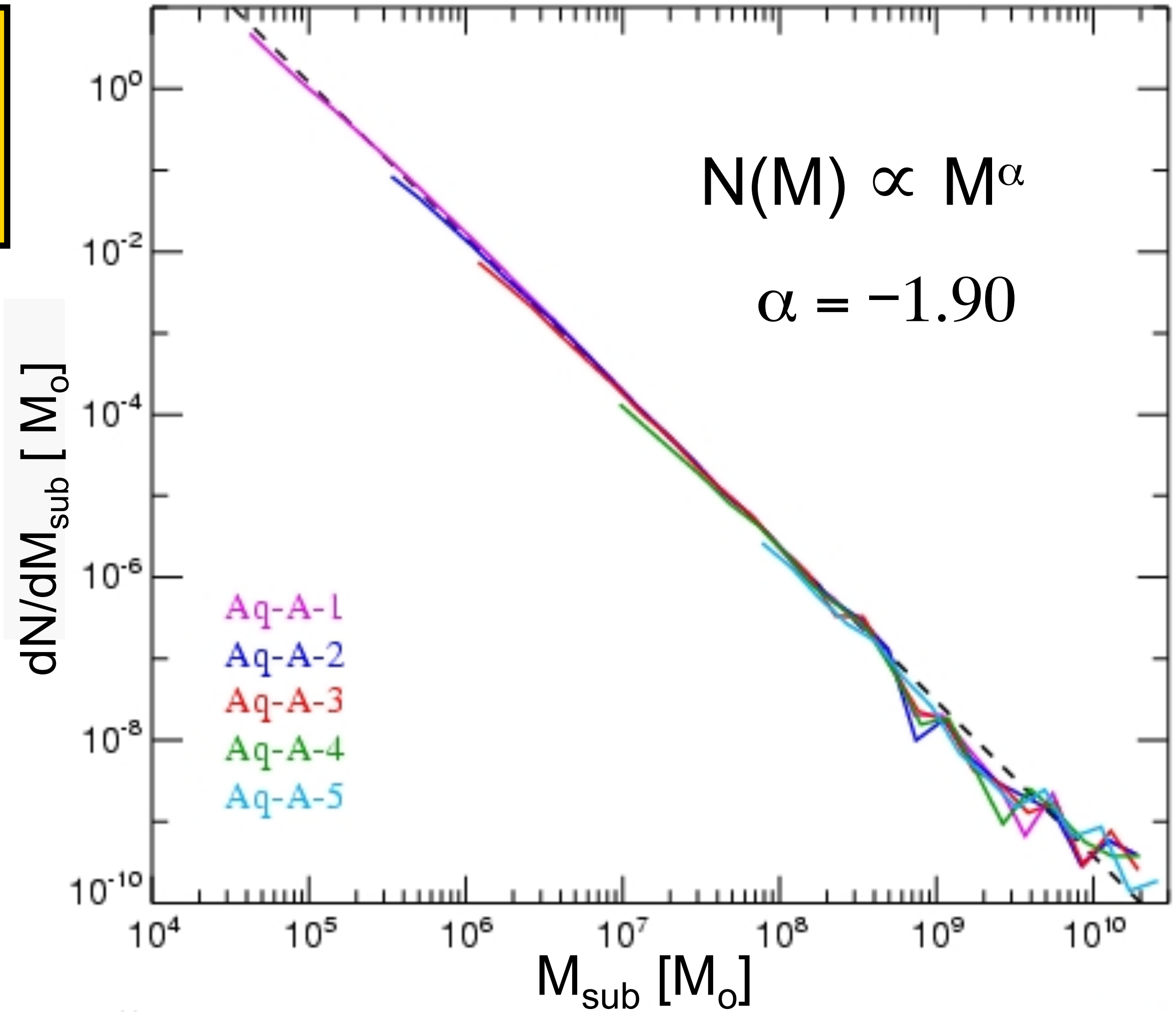
# The mass function of substructures

The subhalo mass function is shallower than $M^2$

- Most of the substructure mass is in the few most massive halos

- The total mass in substructures converges well even for moderate resolution

Virgo consortium
Springel et al 08



300,000 subhalos within virialized region in Aq-A-1

Springel, Wang, Vogelsberger, Ludlow, Jenkins, Helmi, Navarro, Frenk & White ‘08

**Institute for Computational Cosmology**

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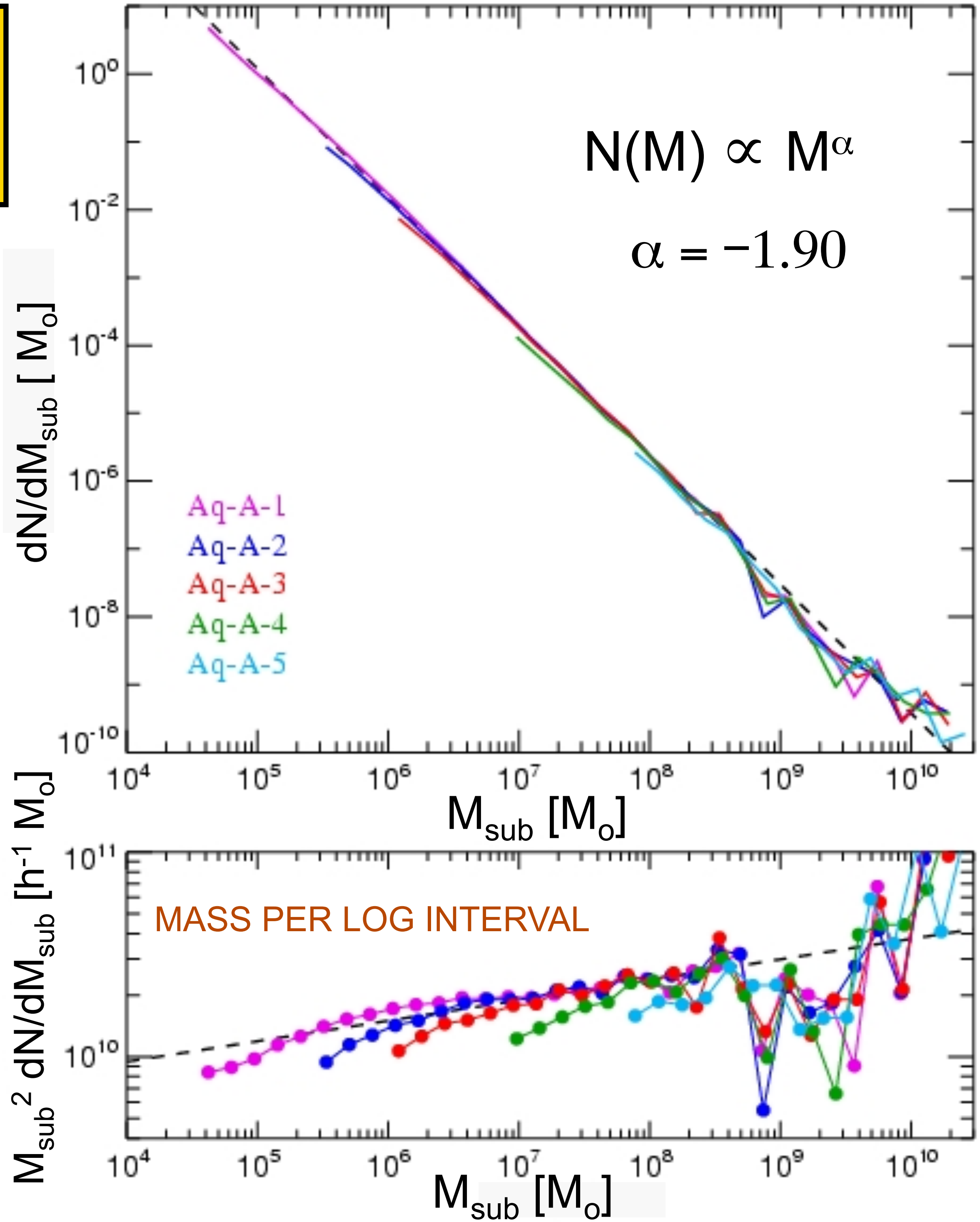
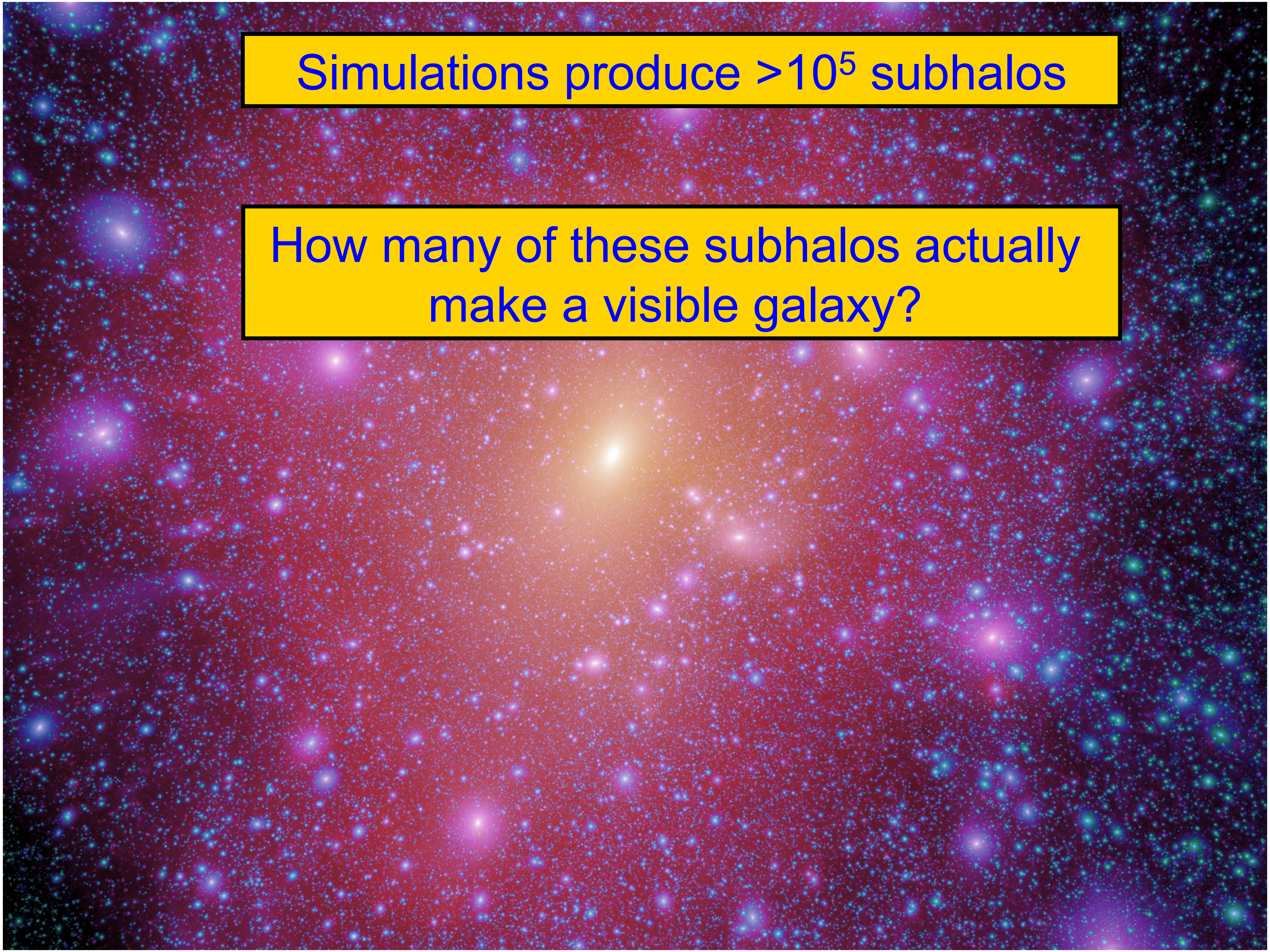
Springel et al 08


$N(M) \propto M^{\alpha}$

$\alpha = -1.90$

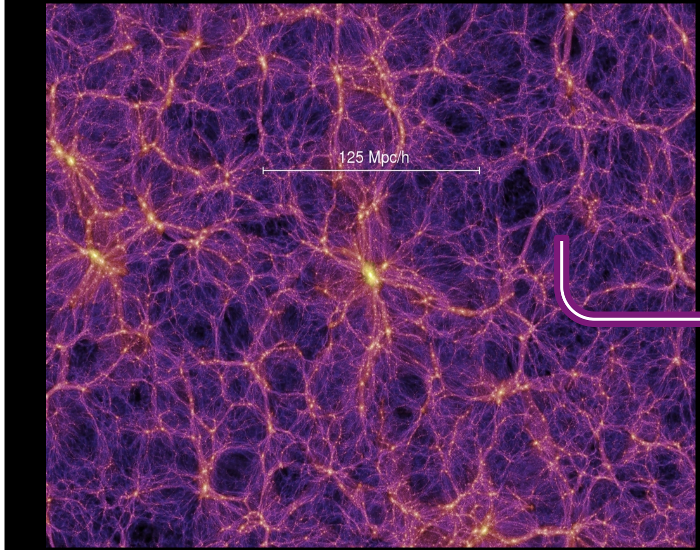
MASS PER LOG INTERVAL



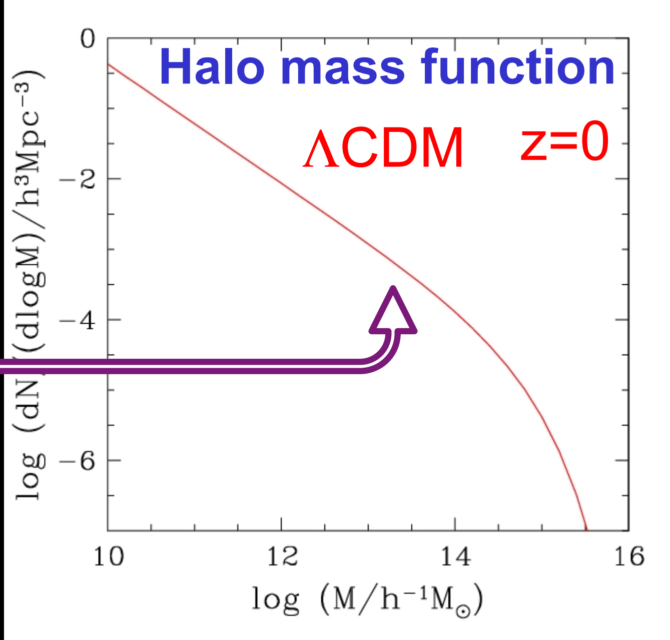
Simulations produce >$10^5$ subhalos

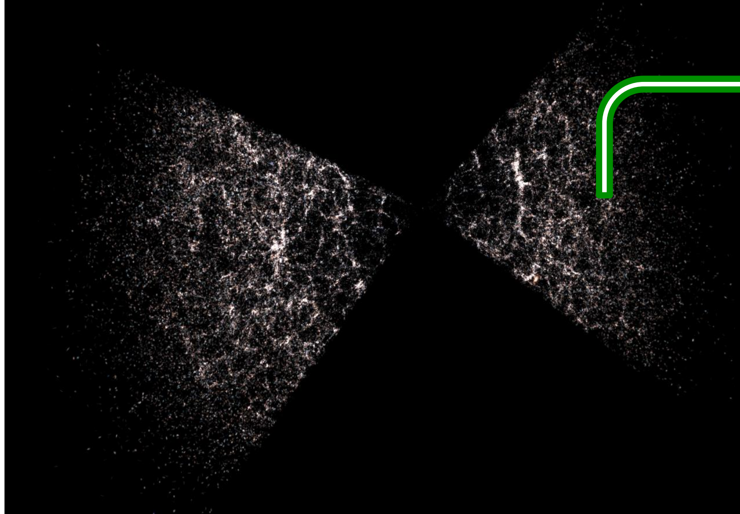
How many of these subhalos actually make a visible galaxy?

# The abundance of dark halos

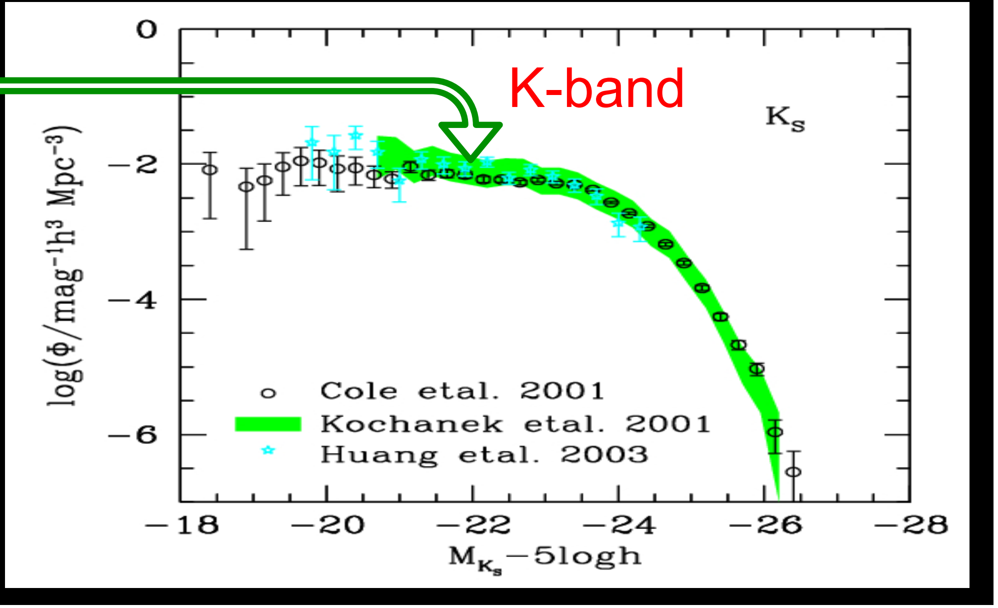


Millennium run





2dFGRS



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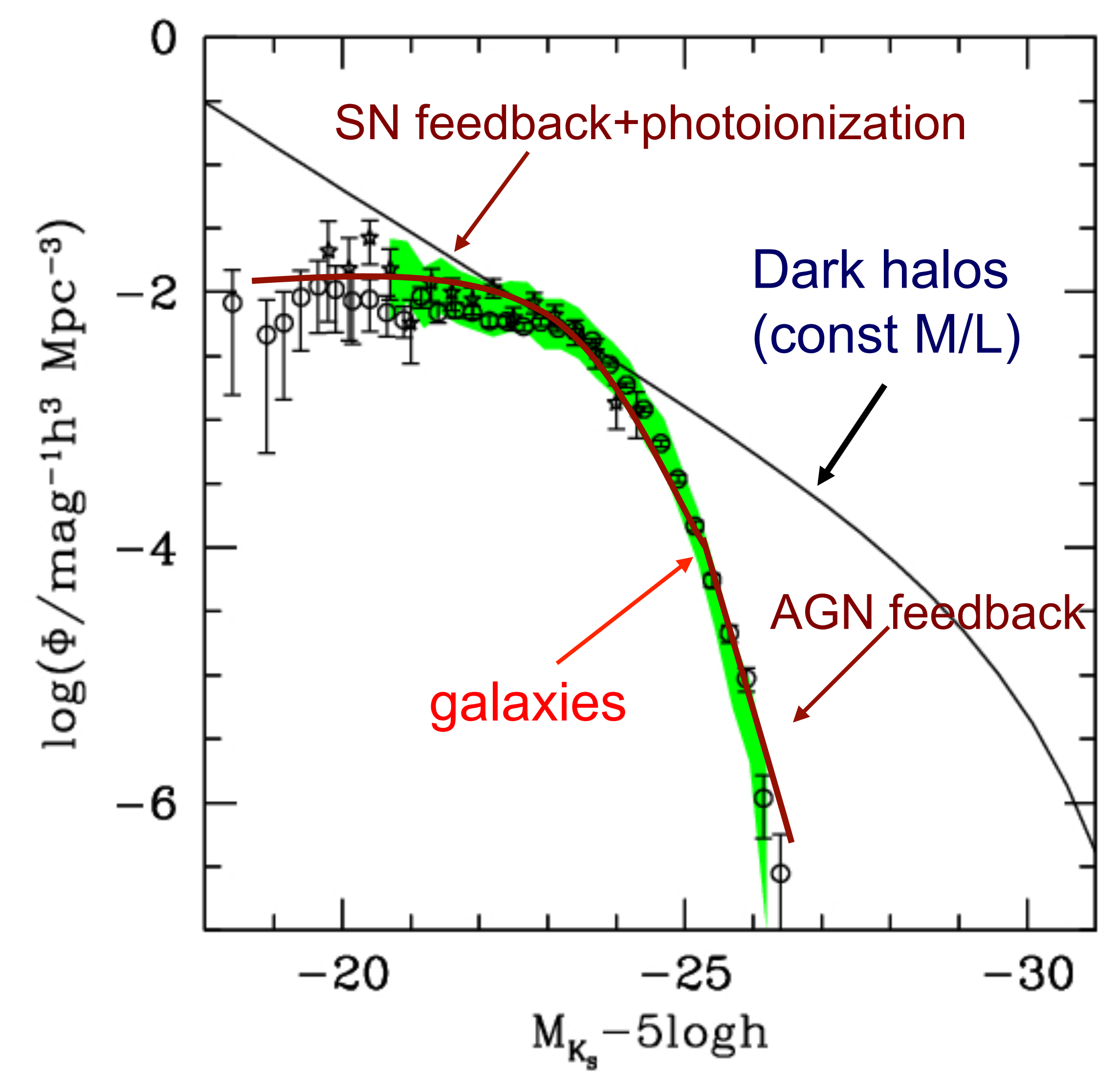
# The galaxy luminosity function

The halo mass function and the galaxy luminosity function have different shapes

⇨

Complicated variation of M/L with halo mass



Benson, Bower, Frenk, Lacey, Baugh & Cole ‘03

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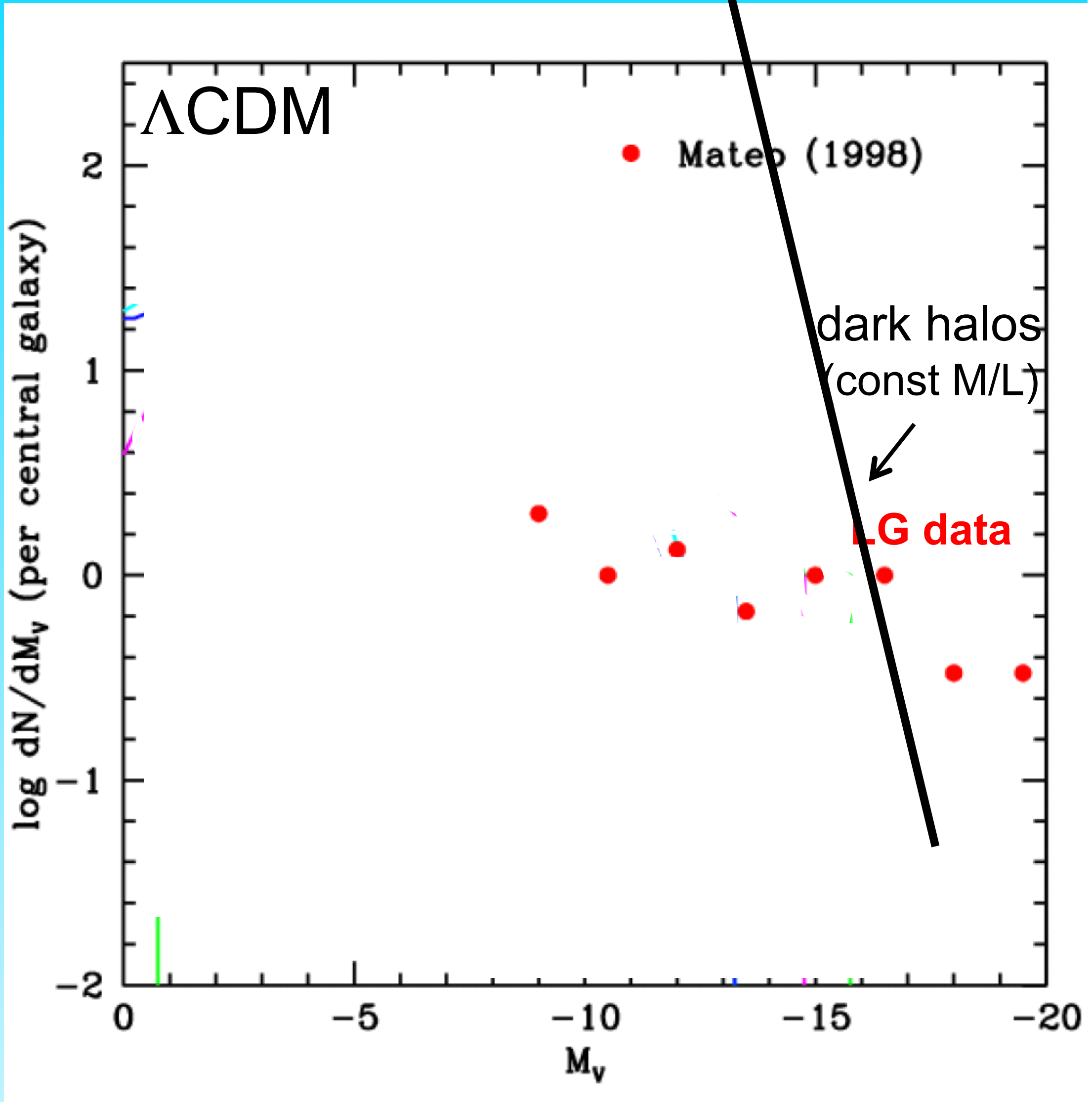
# Luminosity Function of Local Group Satellites



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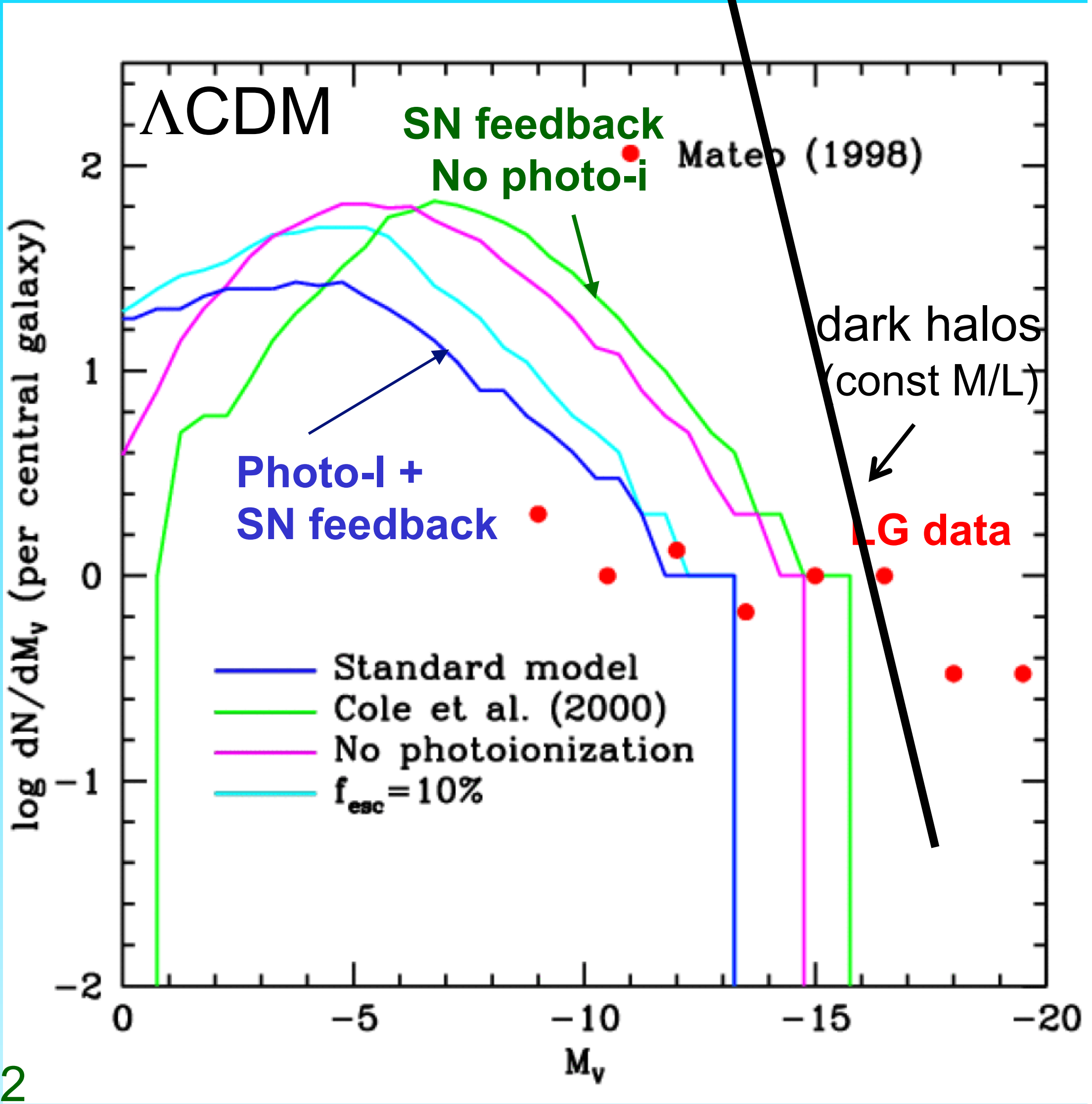
# Luminosity Function of Local Group Satellites

- Photoionization inhibits the formation of satellites
- Abundance of satellies reduced by large factor!
- Median model gives correct abundance of sats brighter than $M_V$=-9, $V_{cir}$ > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites



Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman etal ’93, Bullock etal ’01)

Institute for Computational Cosmology

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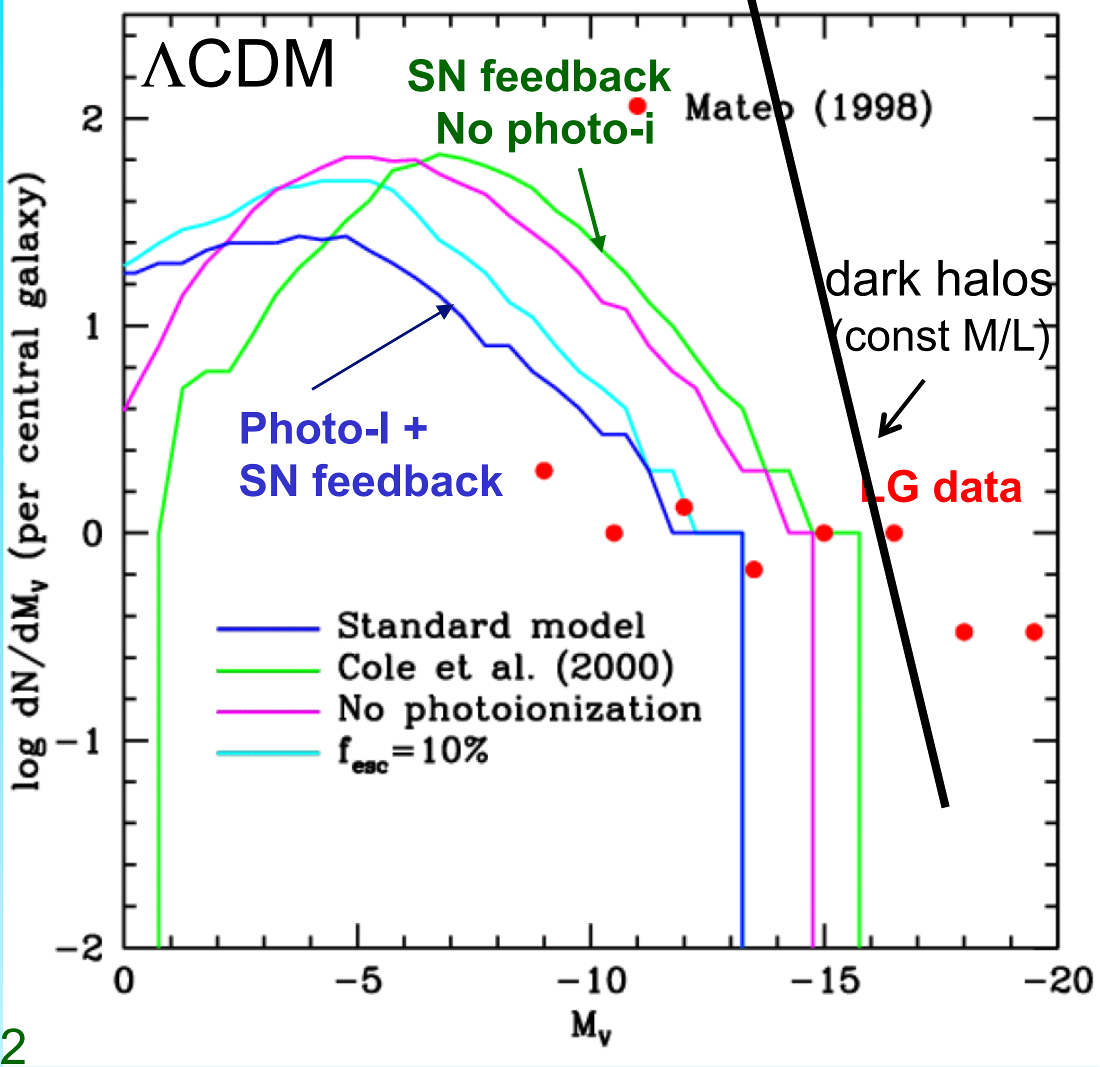

SN feedback
No photo-i

Photo-I +
SN feedback

dark halos
(const M/L)

LG data

Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman etal ’93, Bullock etal ’01)

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# The satellites of the Milky Way

| Name | Year discovered |
|---|---|
| LMC | 1519 |
| SMC | 1519 |
| Sculptor | 1937 |
| Fornax | 1938 |
| Leo II | 1950 |
| Leo I | 1950 |
| Ursa Minor | 1954 |
| Draco | 1954 |
| Carina | 1977 |
| Sextans | 1990 |
| Sagittarious | 1994 |

# The satellites of the Milky Way

Several new satellites discovered in the past few years

| Name | Year discovered |
|---|---|
| LMC | 1519 |
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| Sculptor | 1937 |
| Fornax | 1938 |
| Leo II | 1950 |
| Leo I | 1950 |
| Ursa Minor | 1954 |
| Draco | 1954 |
| Carina | 1977 |
| Sextans | 1990 |
| Sagittarious | 1994 |

| Name | Year discovered |
|---|---|
| Canis Major | 2003 |
| Ursa Major I | 2005 |
| Wilman I | 2005 |
| Ursa Major II | 2006 |
| Bootes | 2006 |
| Canes Venatici I | 2006 |
| Canes Venatici II | 2006 |
| Coma | 2006 |
| Leo IV | 2006 |
| Hercules | 2006 |
| Leo T | 2007 |
| Segue I | 2007 |
| Boo II | 2007 |
| Segue II | 2009 |

# Luminosity Function of Local Group Satellites

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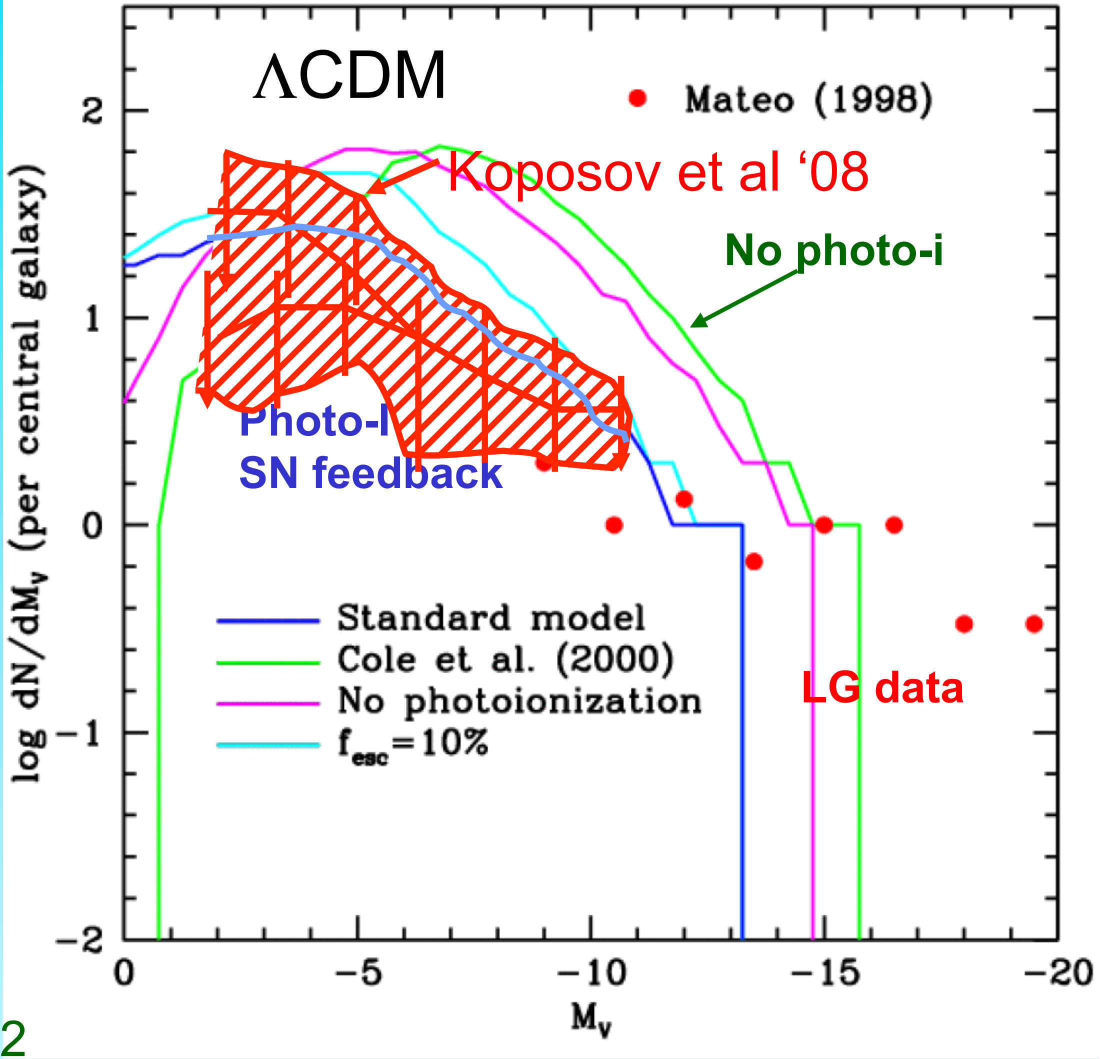

Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman etal '93, Bullock etal '01)

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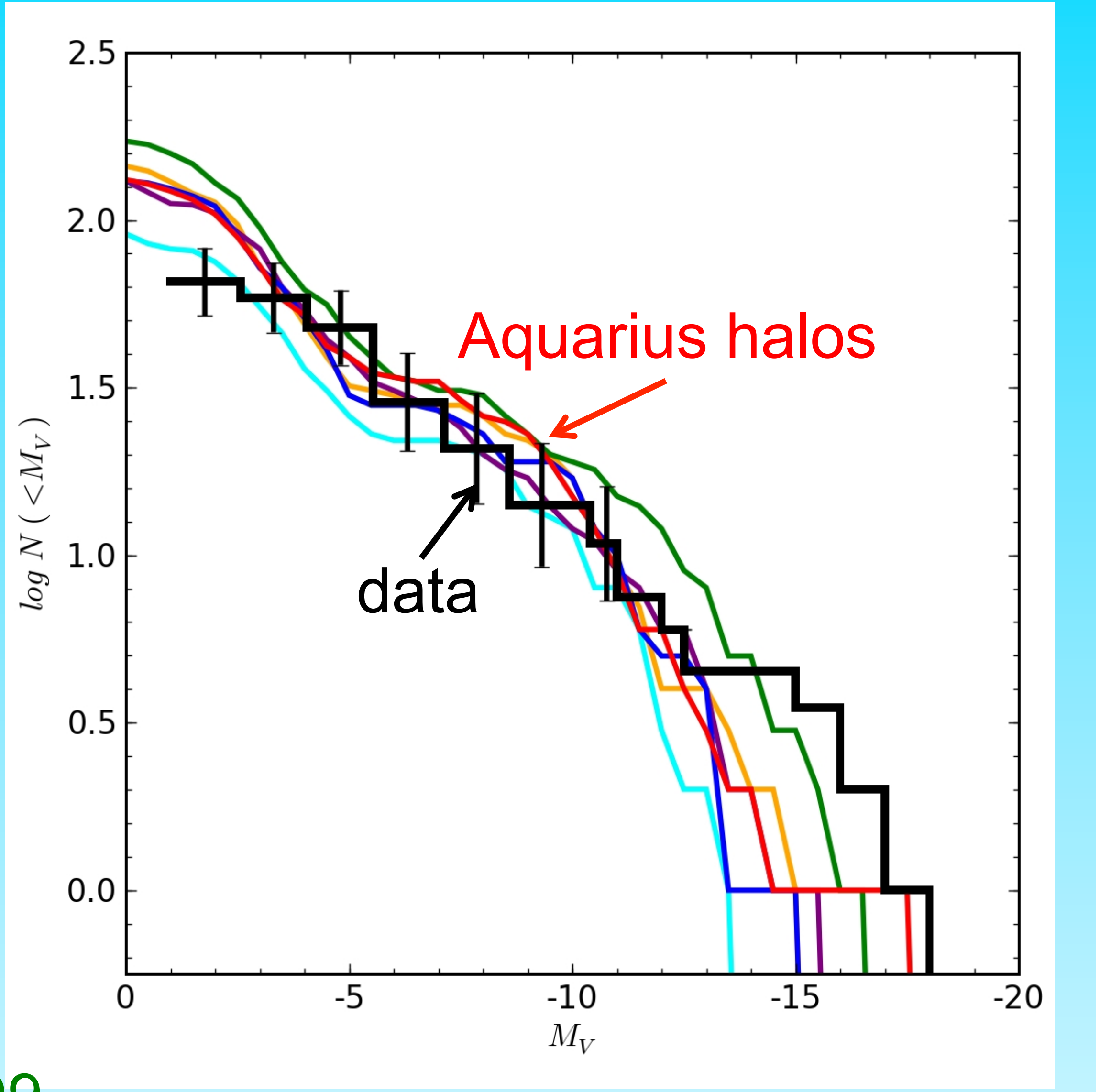
# Luminosity function of Milky Way satellites

Semi-analytic modelling

Reionization as in the Okamoto et al simulations



Cooper, Cole, Frenk et al '09

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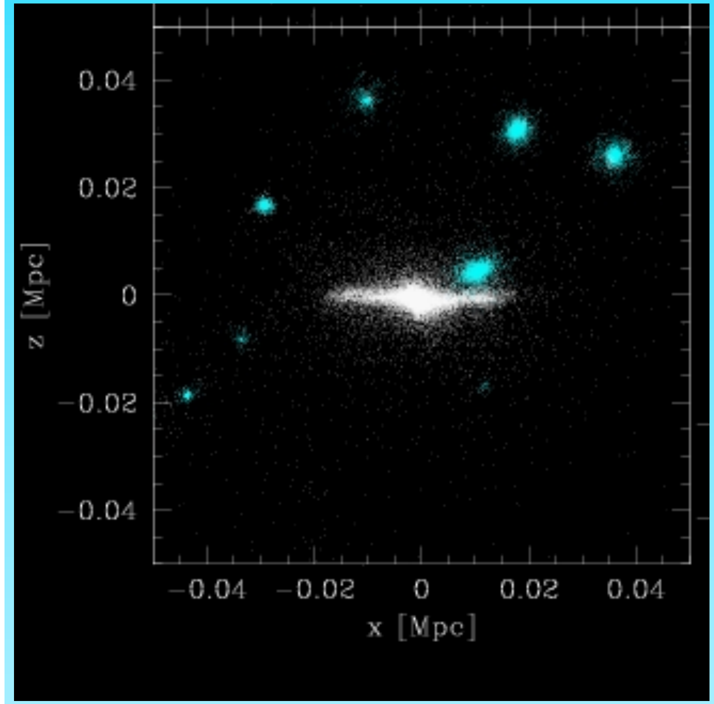
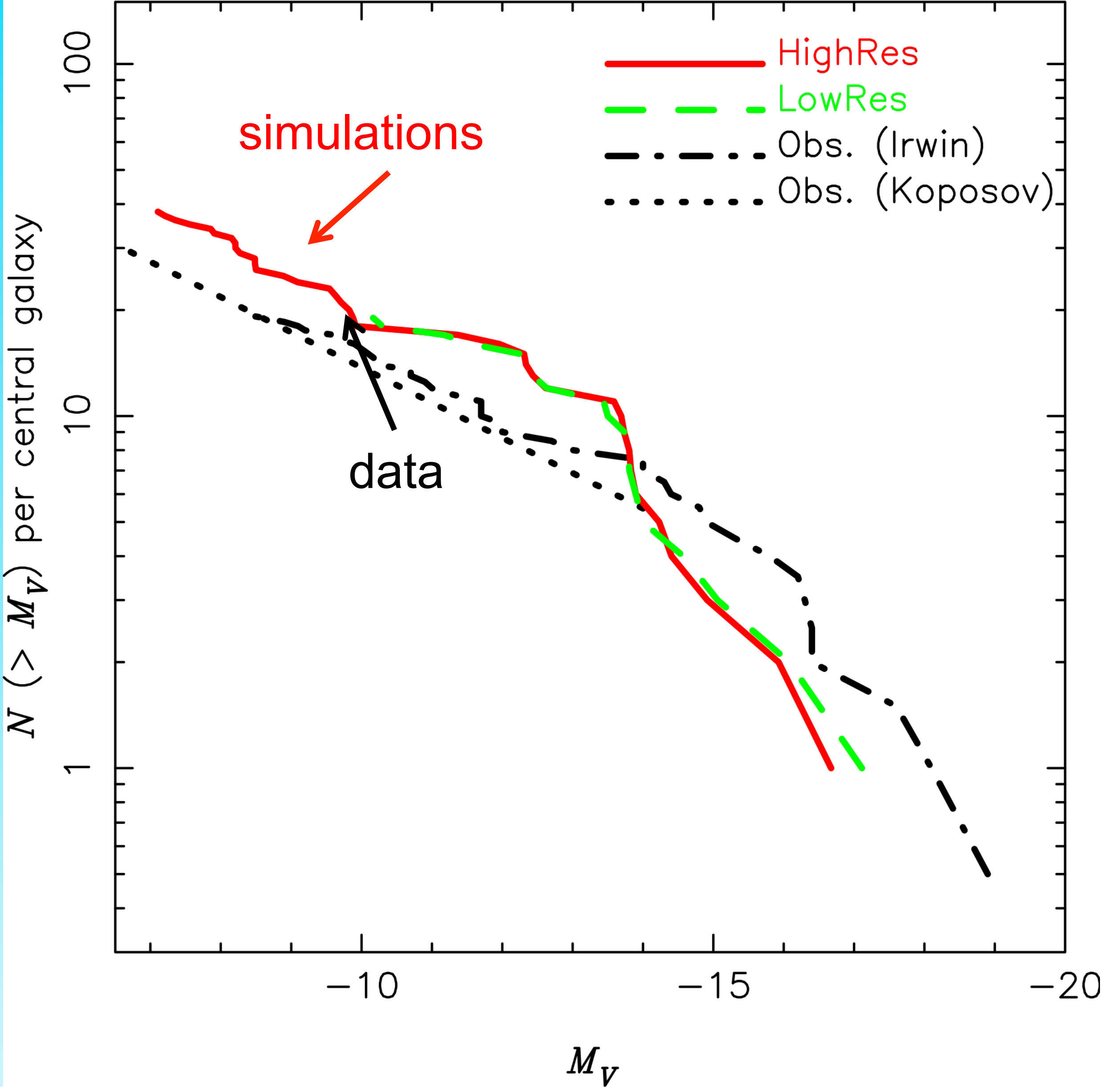
# Luminosity function of Milky Way satellites

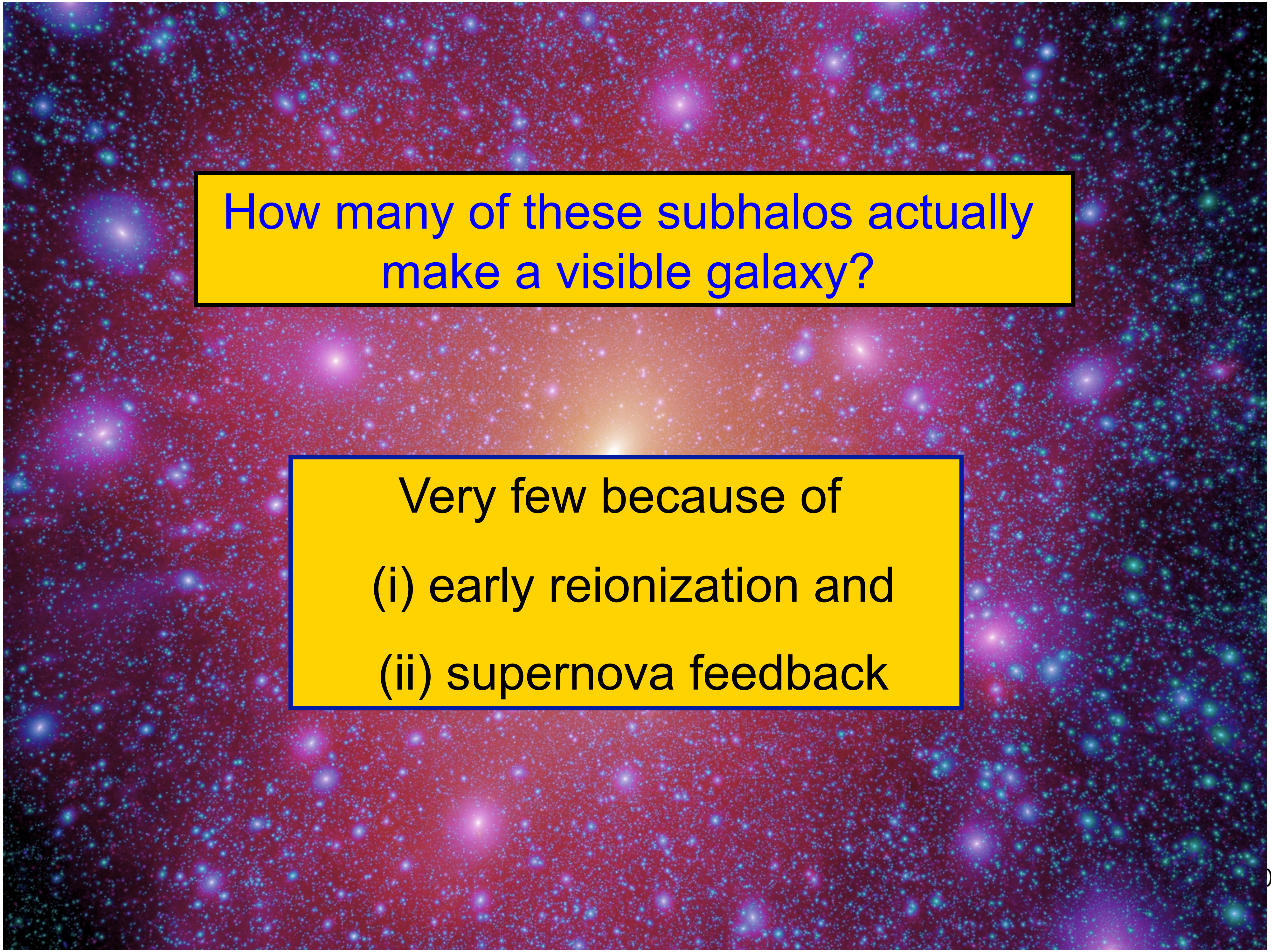
Hydrodynamic sims in Aquarius halos



Note: ultra-faint satellites not resolved in simulation

Okamoto & Frenk '09





How many of these subhalos actually make a visible galaxy?

Very few because of

(i) early reionization and

(ii) supernova feedback

# The stellar halo of the Milky Way

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# The Milky Way and the nature of the dark matter

- Test CDM predictions on galaxy scales
  - Structure of dark matter halos
  - Number of satellite galaxies
  - Remnants of hierarchical formation (streams)

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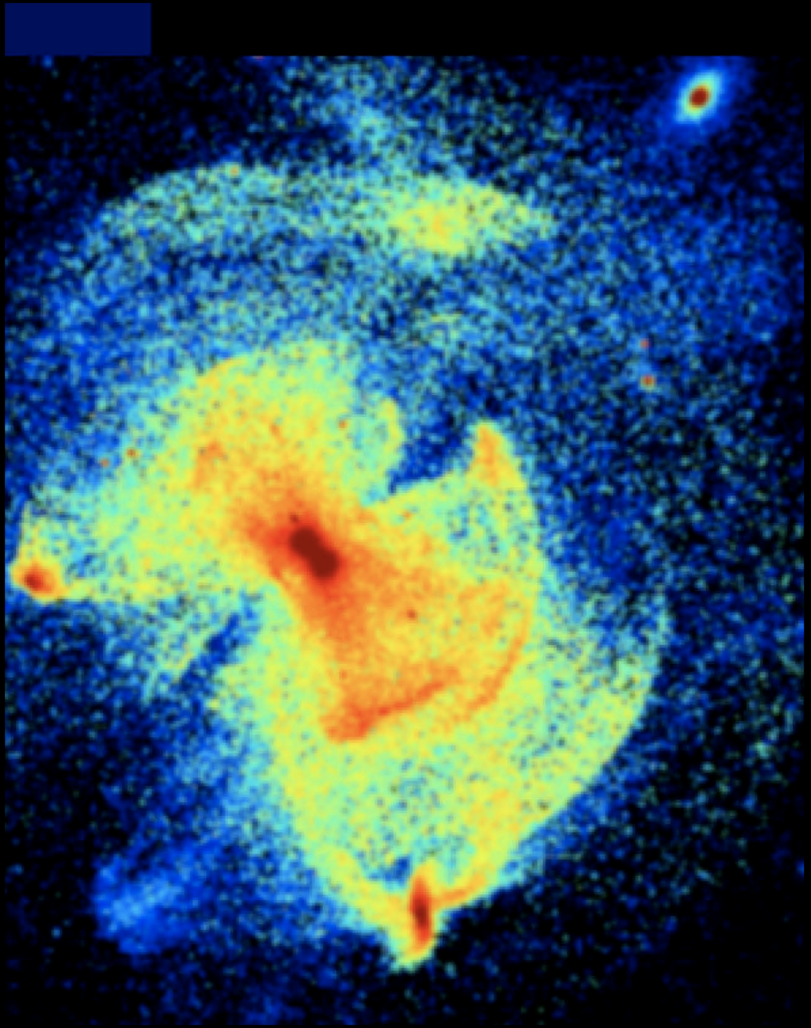
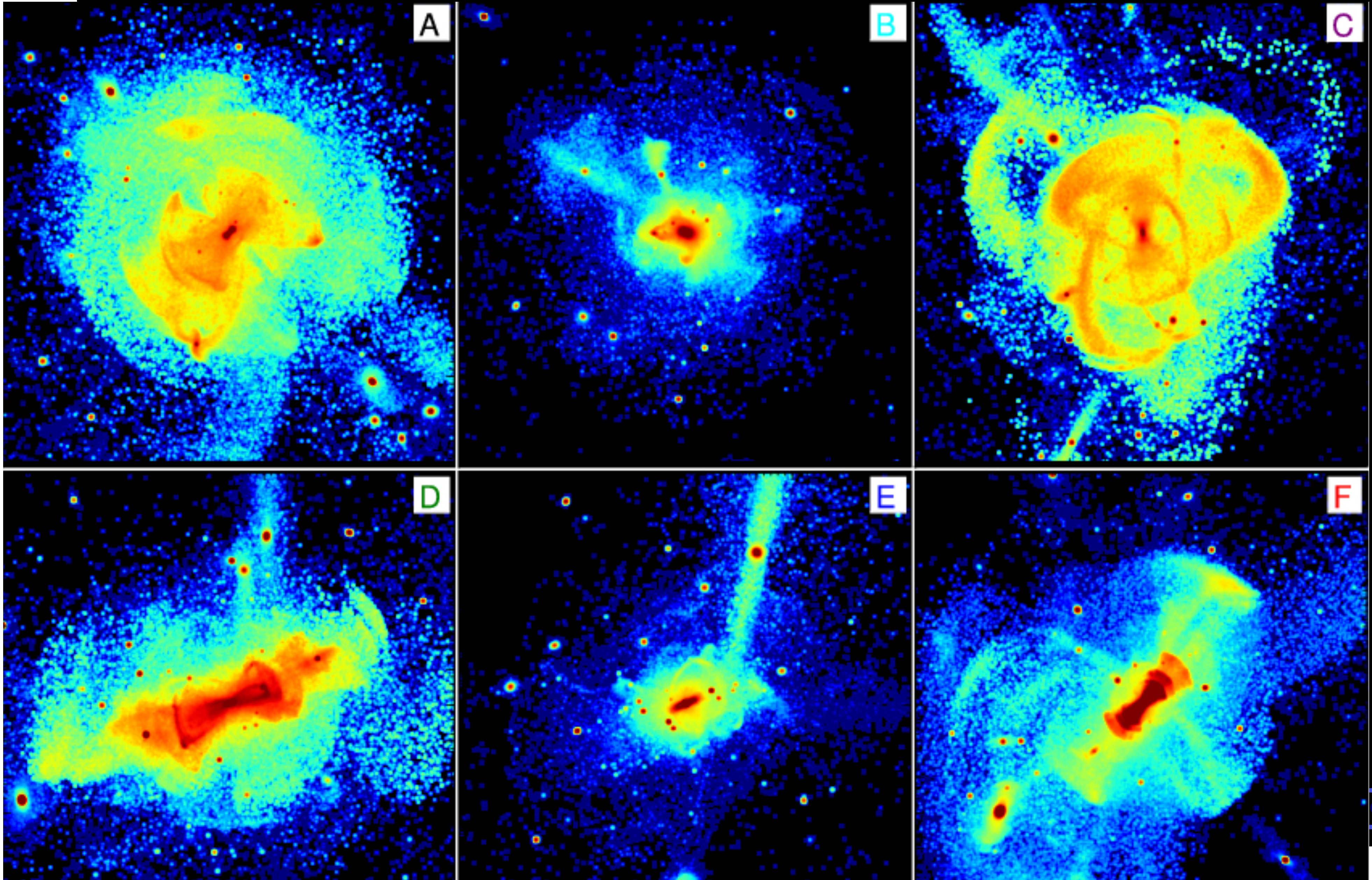


Aquarius dark matter simulation + stars

Cooper et al ‘10

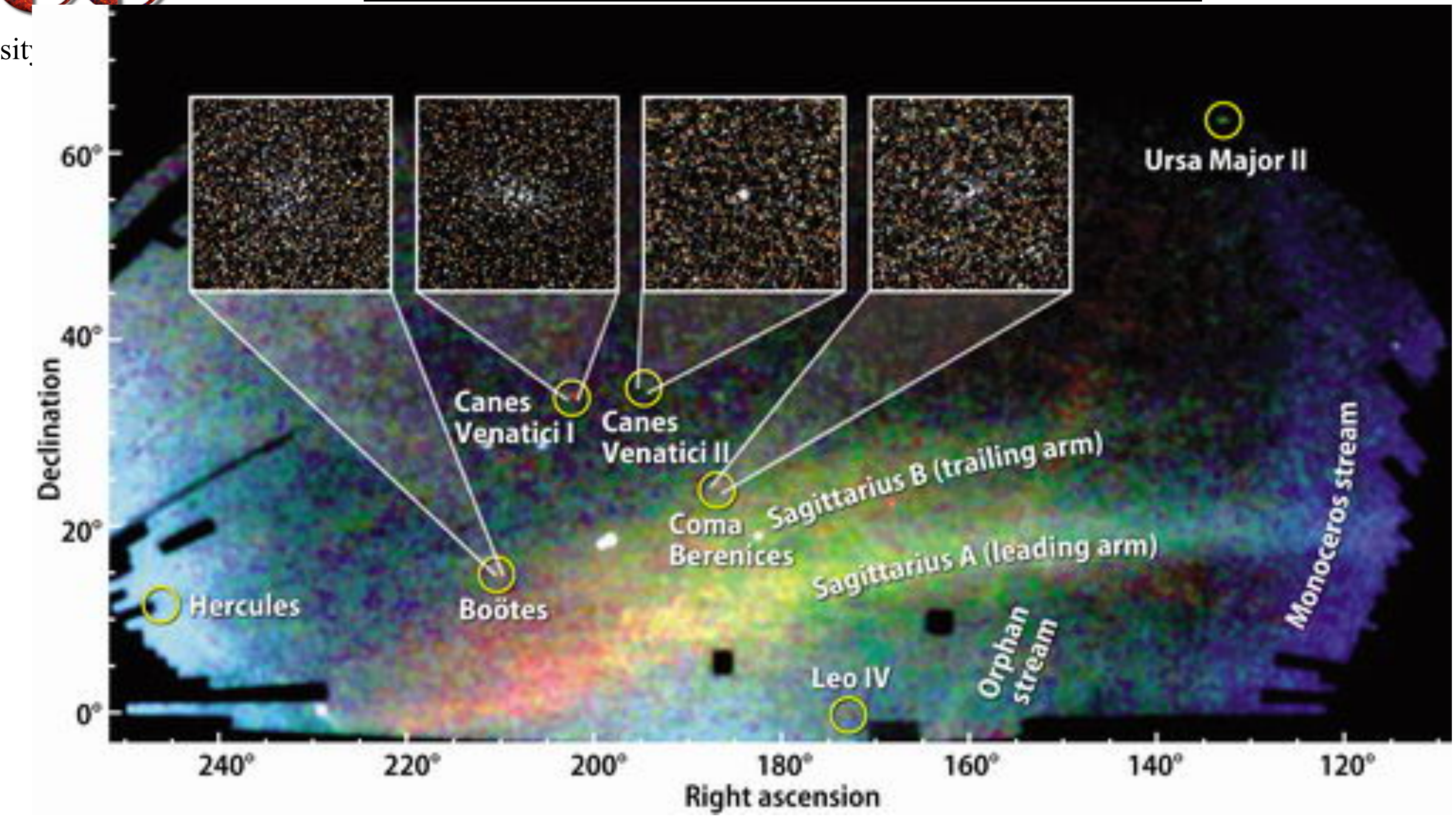


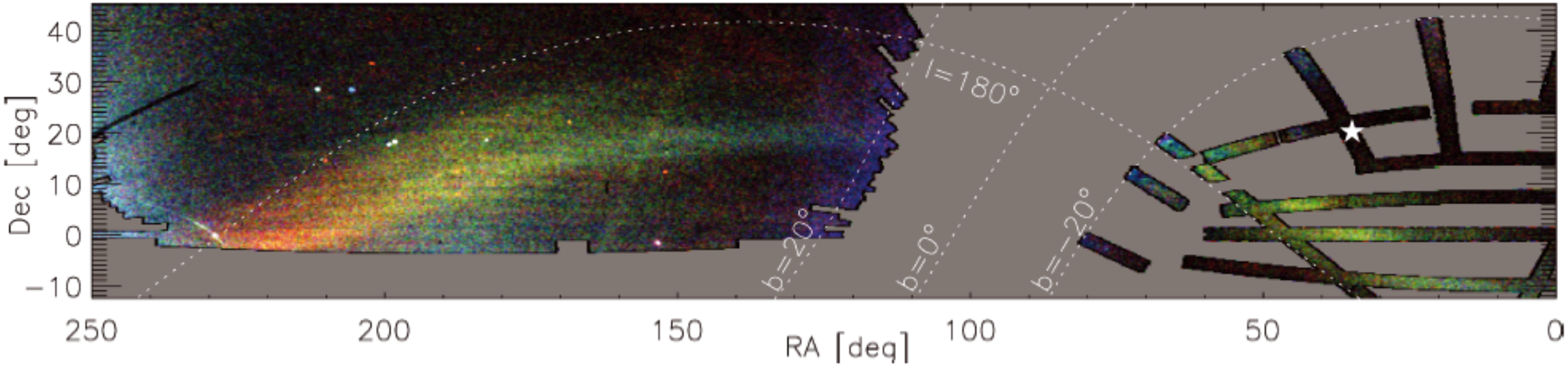
ology

# Tidal streams

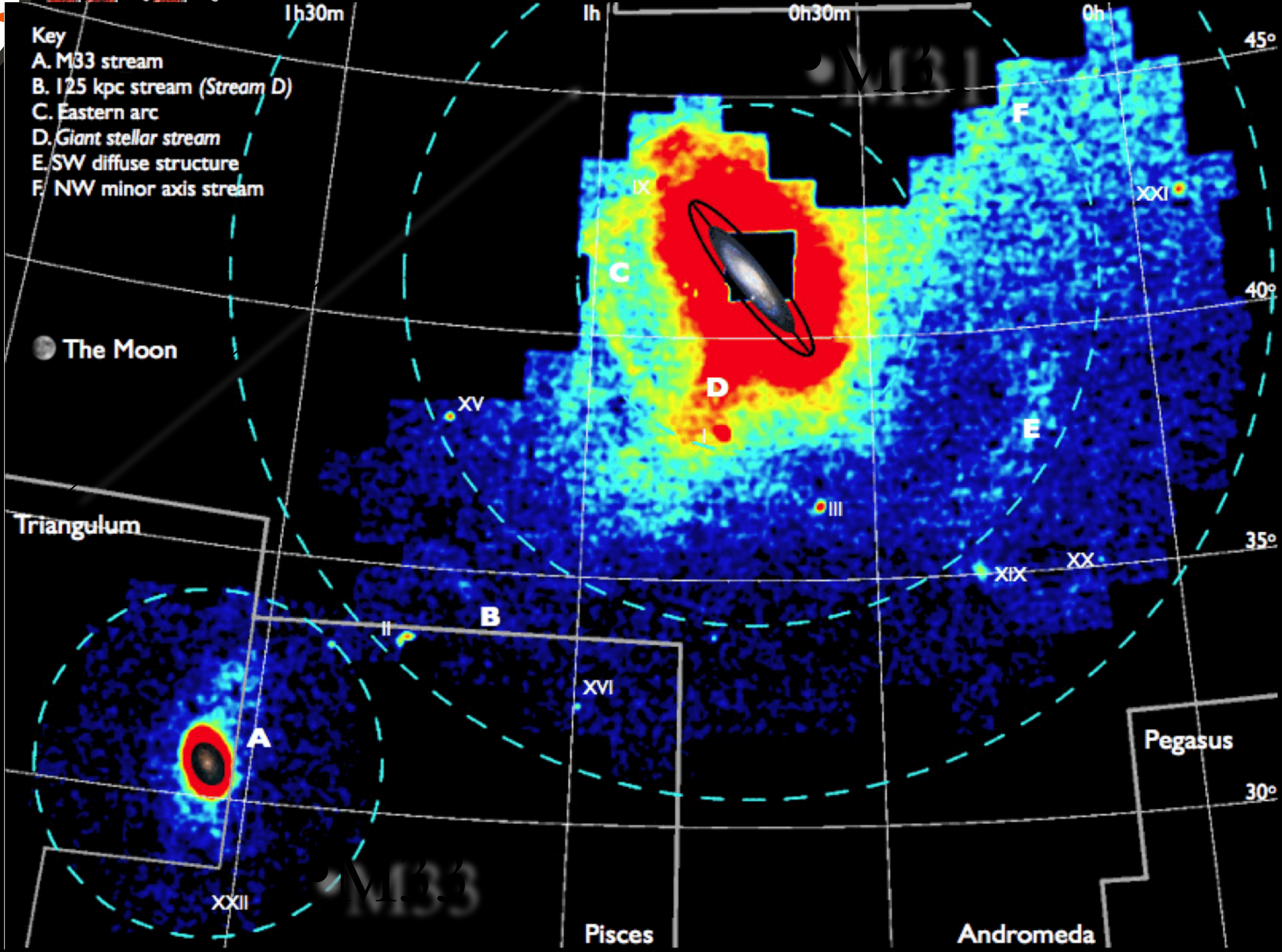
The field of streams

Belokurov et al ‘07

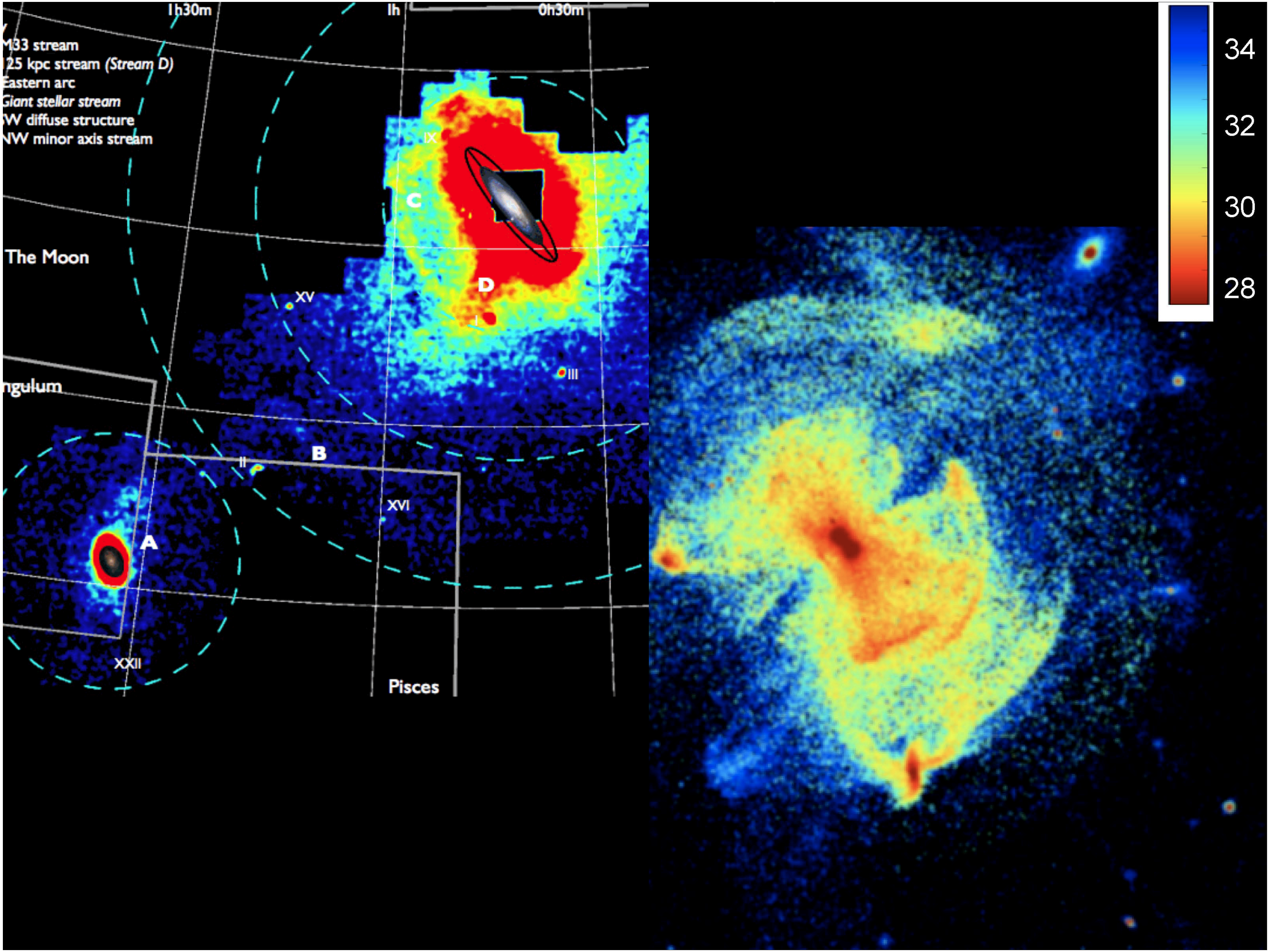




# The PANDA survey of M31

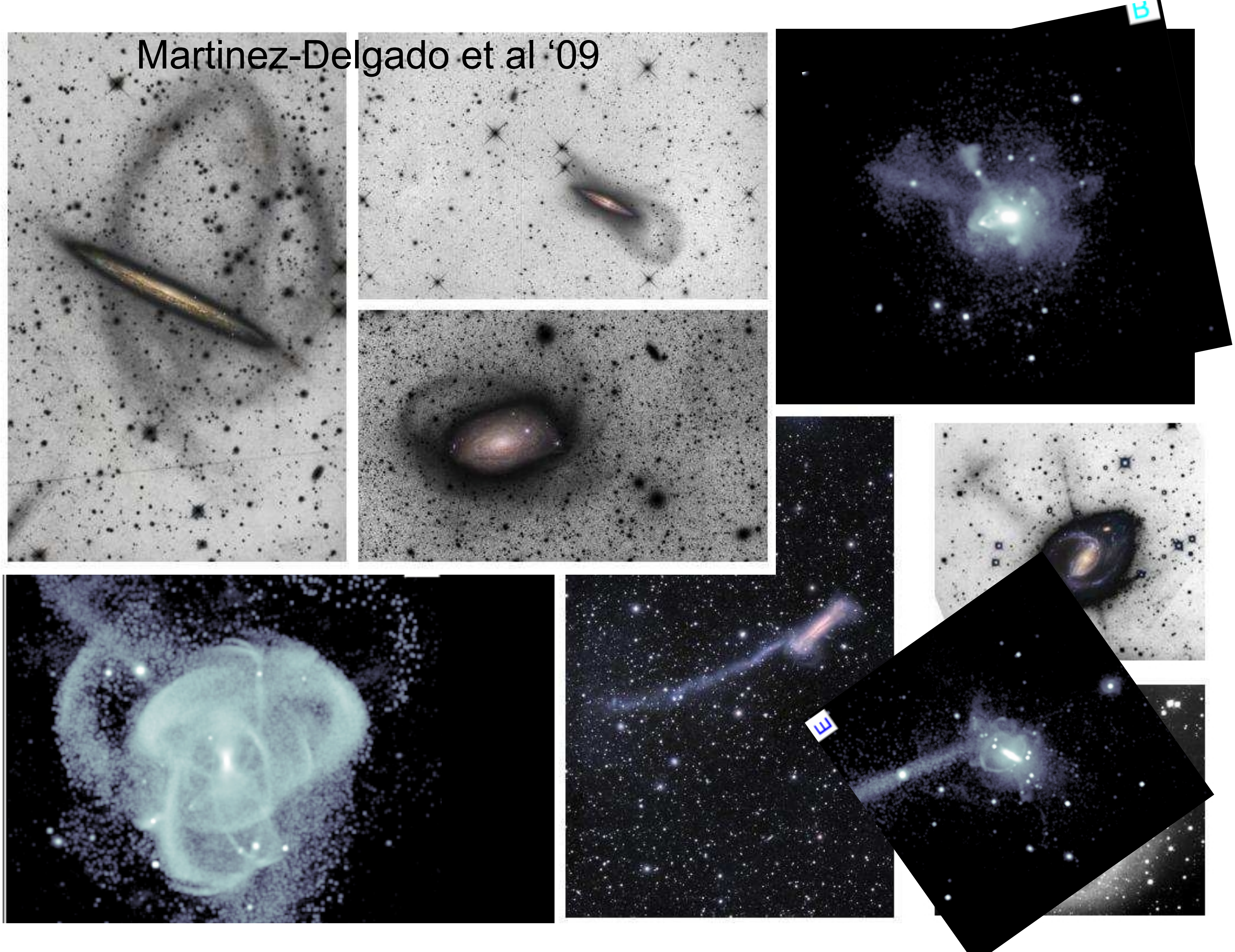


McConnachie, Ibata Navarro, Widrow, Babul … ‘09



1h30m
1h
0h30m
M33 stream
125 kpc stream (Stream D)
Eastern arc
Giant stellar stream
W diffuse structure
NW minor axis stream
The Moon
ngulum
IX
C
D
I
XV
III
B
II
XVI
A
XXII
Pisces
34
32
30
28

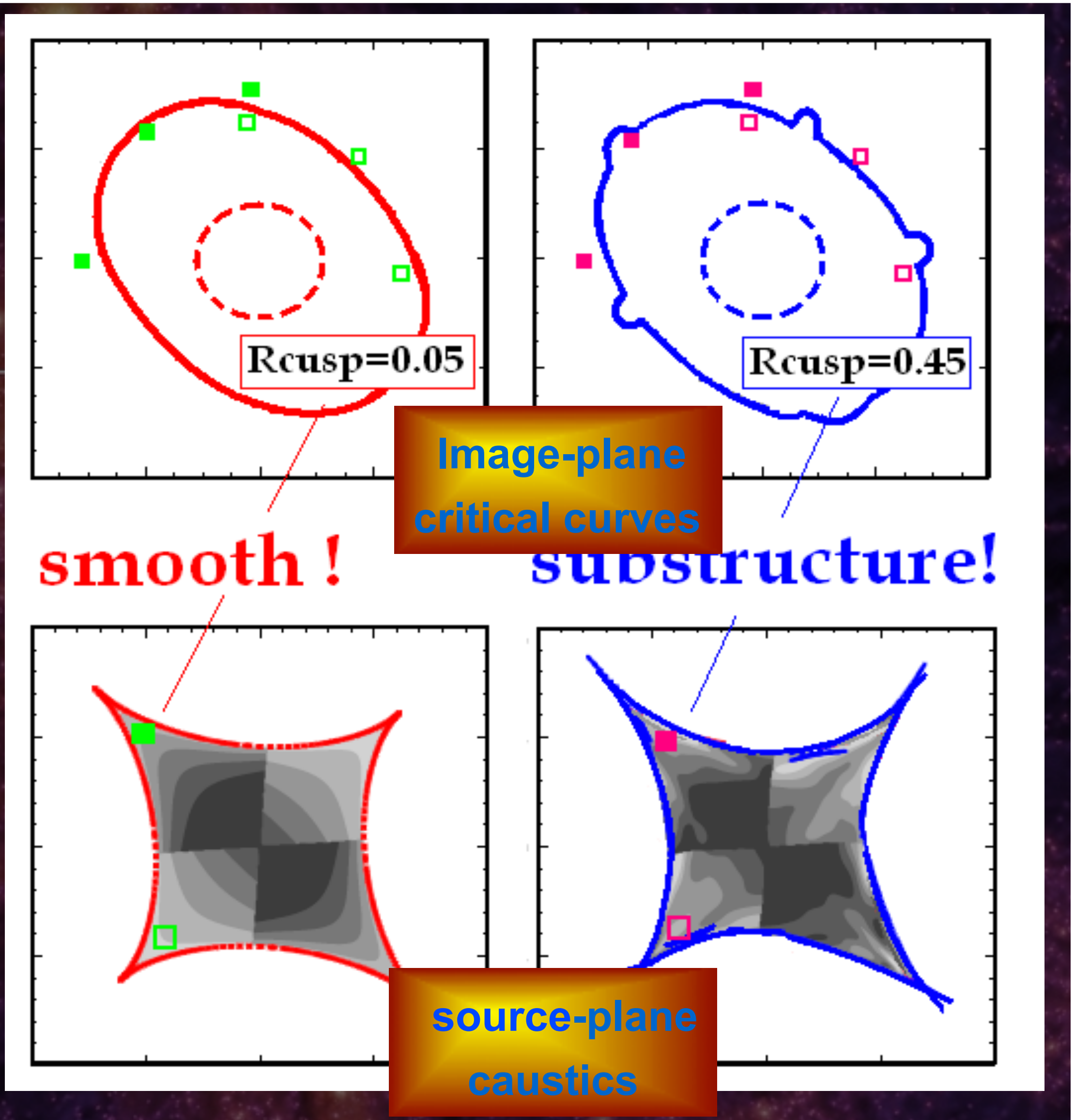
Martinez-Delgado et al ‘09



If CDM is right, the dark subhalos must be there !

Is there any way to find them?

- Background QSO aligned with lens → caustic
- Sources near cusp obey flux cusp-caustic relation if lens is smooth
- If lens is lumpy → flux-anomaly
- Cusp-caustic relation violation seen in 3 multiply-imaged quasars

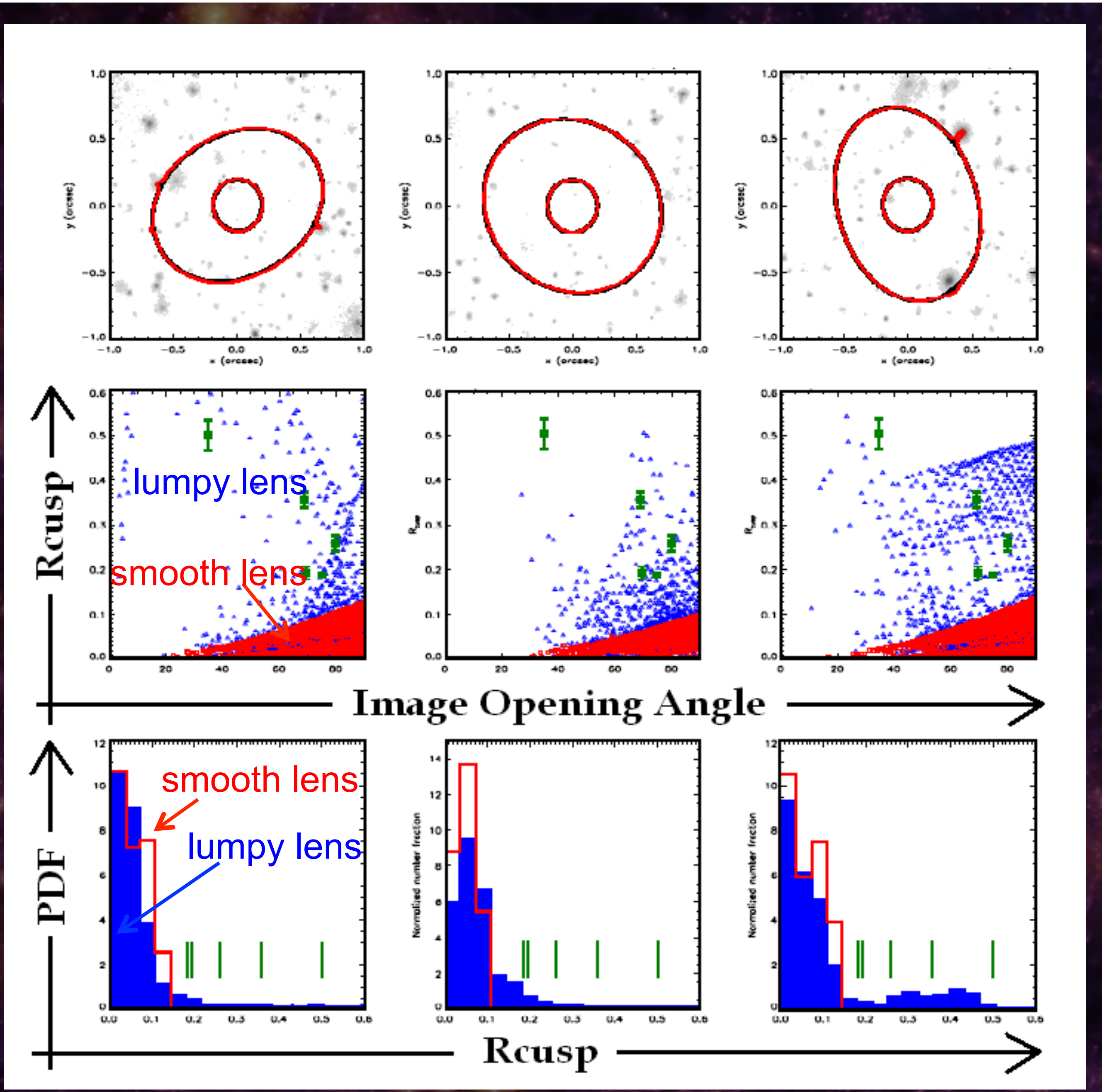


- Dandan Hu + Aquarius '09 '10

$$R_{cusp} = (|\mu_A+\mu_B+\mu_C|) / (|\mu_A|+|\mu_B|+|\mu_C|)$$

$R_{cusp}$ --> 0, when total $\mu$ --> infinity

- 3/5 QSOs caustic lenses ($\Delta\theta \lesssim 90^\circ$) show violation due to substructures.
- Observed violation is too strong ($P_{obs} < 0.01$) !
- CDM halos DO NOT have enough substructure in inner parts



Dandan Hu + Aq '09, '10

# A blueprint for detecting halo CDM

Supersymmetric particles annihilate and lead to production of $\gamma$-rays which may be observable by GLAST/FERMI

Intensity of annihilation radiation at $\boldsymbol{x}$ depends on:

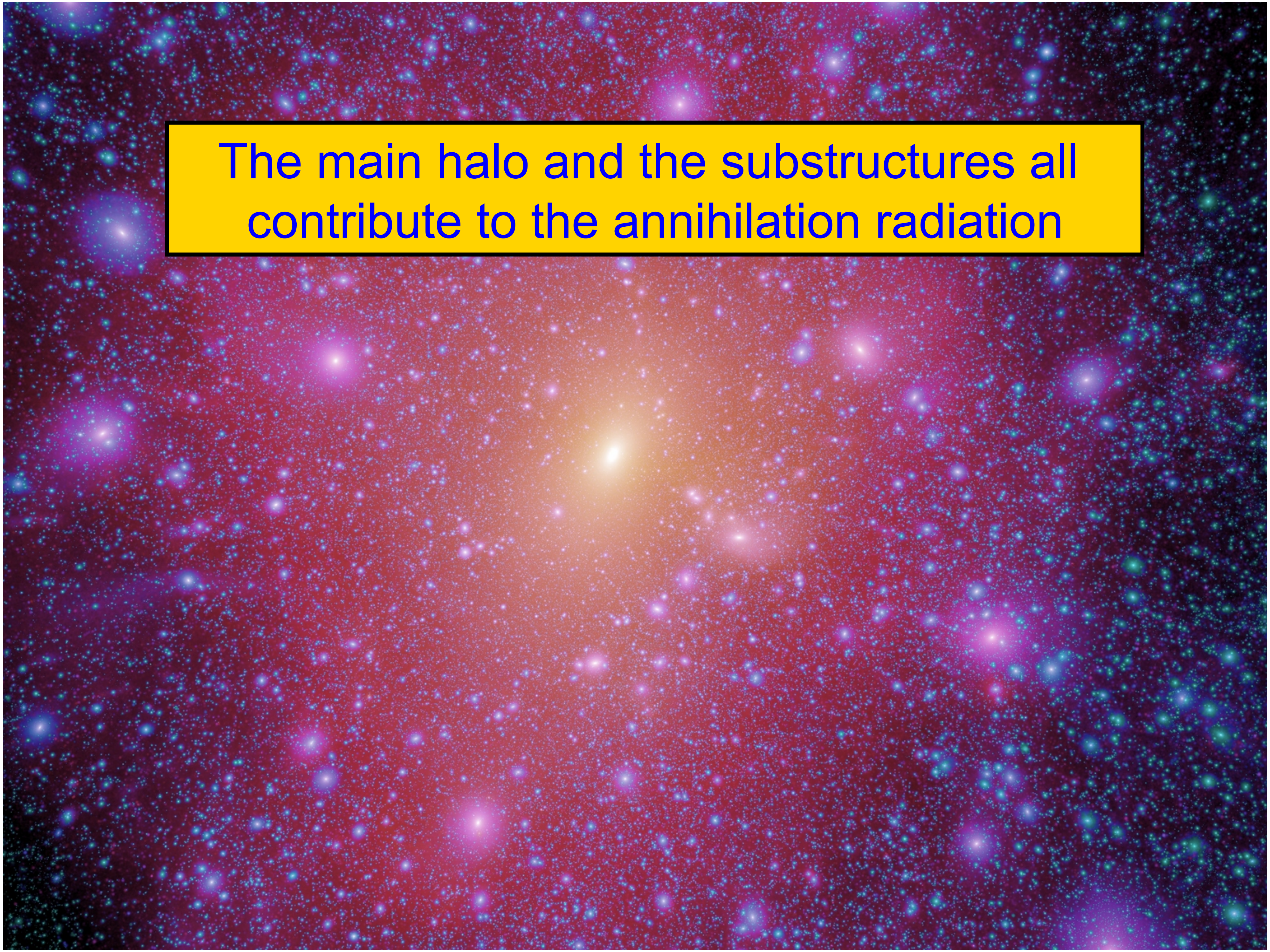
$$\int \underbrace{\rho^2(\boldsymbol{x})}_{\text{halo density at } \boldsymbol{x}} \; \underbrace{\langle \sigma v \rangle}_{\text{cross-section}} \, dV$$

halo density at $\boldsymbol{x}$
(astrophysics)

cross-section
(particle physics)

⇒ Theoretical expectation requires knowing $\rho(\boldsymbol{x})$

⇒ Accurate high resolution N-body simulations of halo formation from CDM initial conditions



The main halo and the substructures all contribute to the annihilation radiation

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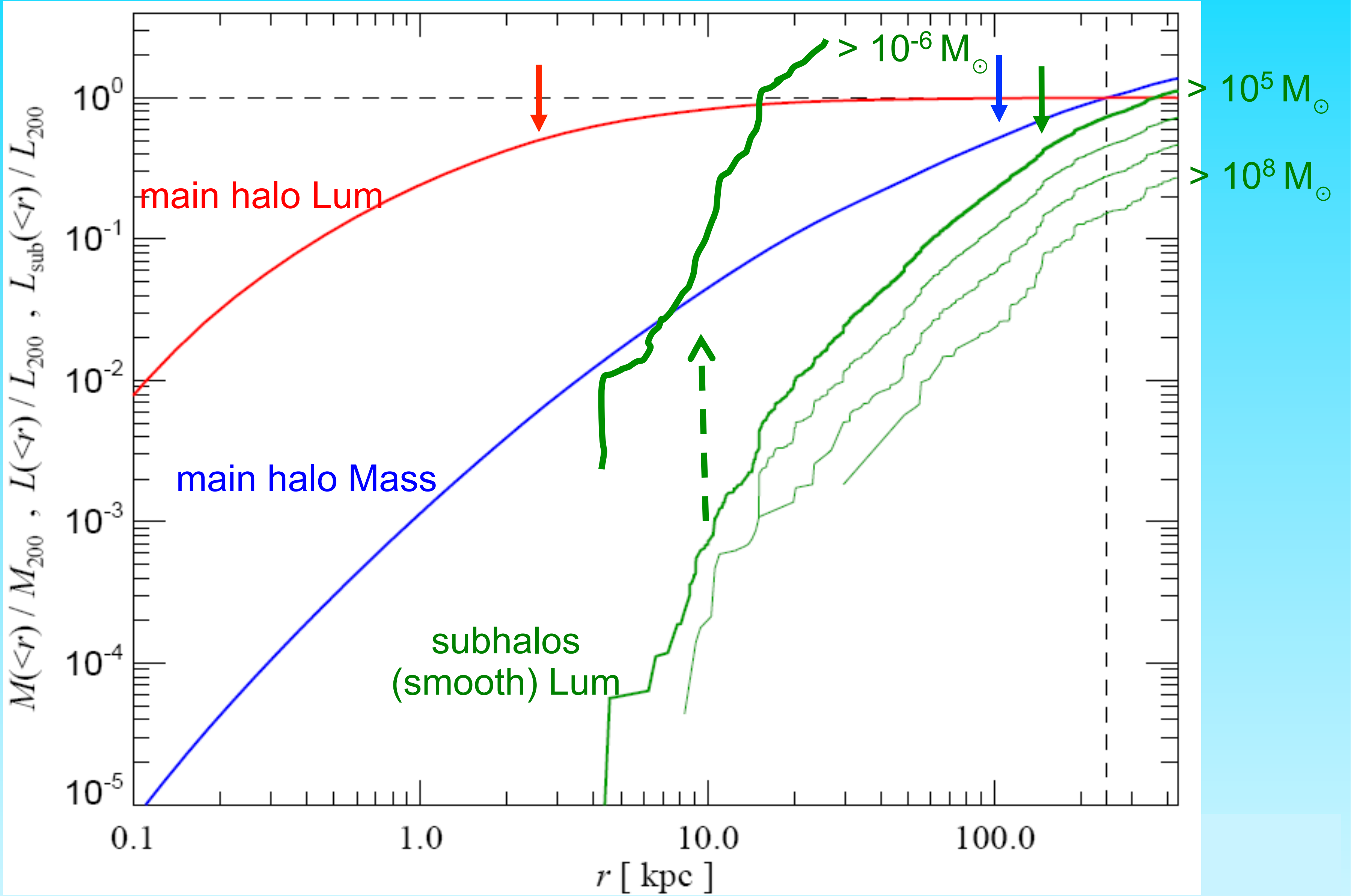
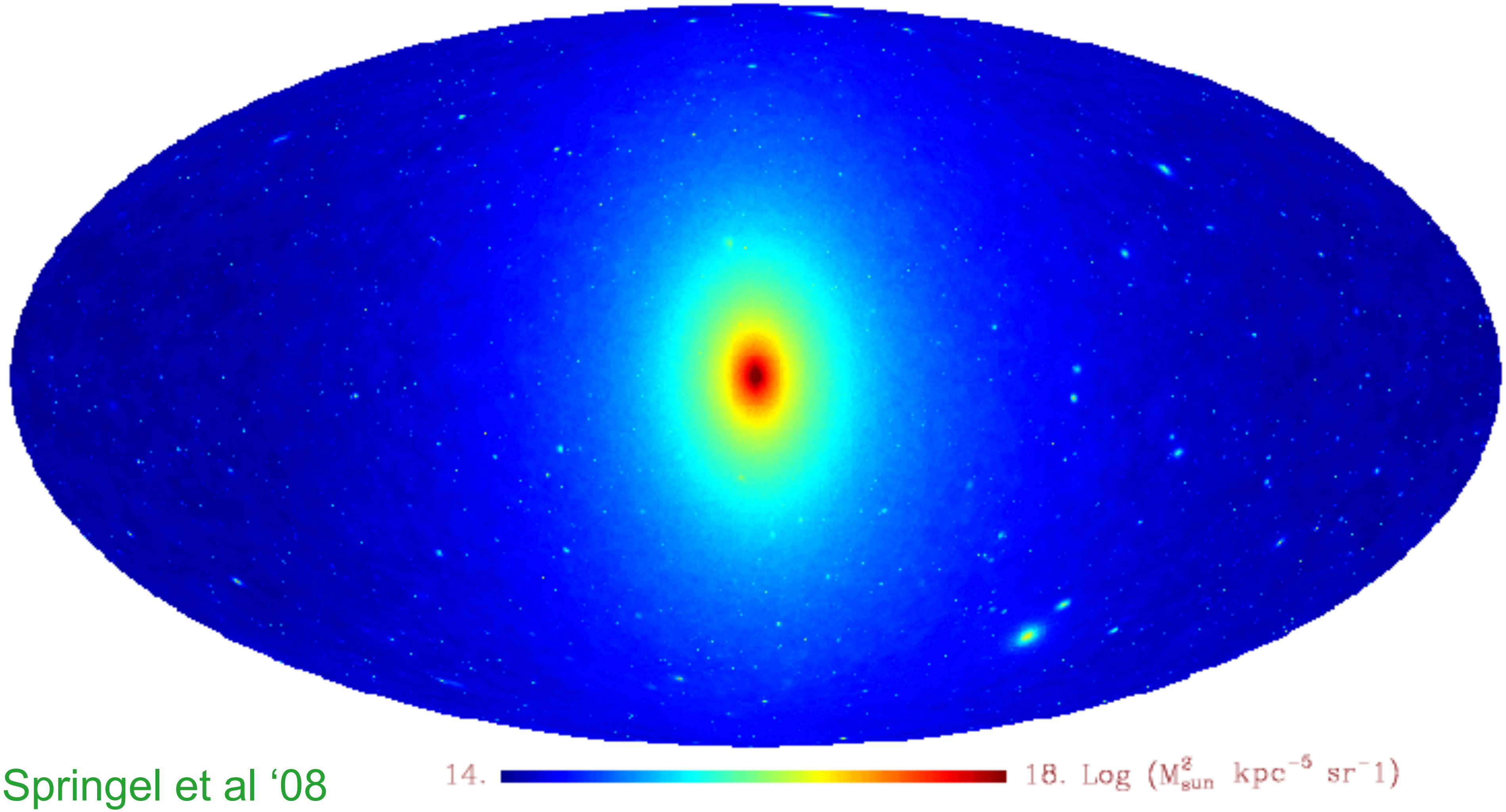
# Mass and annihilation radiation profiles of a MW halo



# The Milky Way seen in annihilation radiation

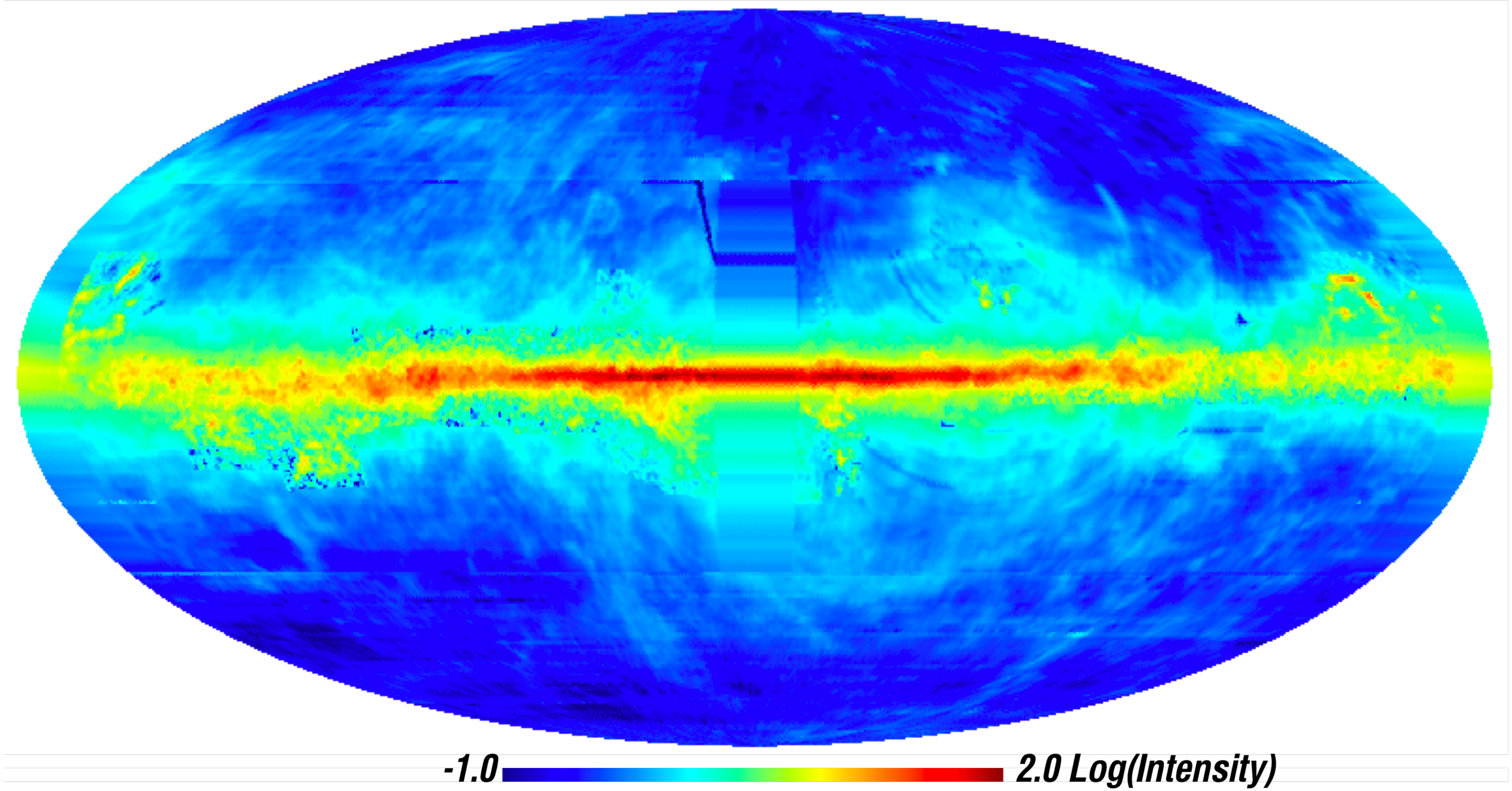
Aquarius simulation: $N_{200} = 1.1 \times 10^9$



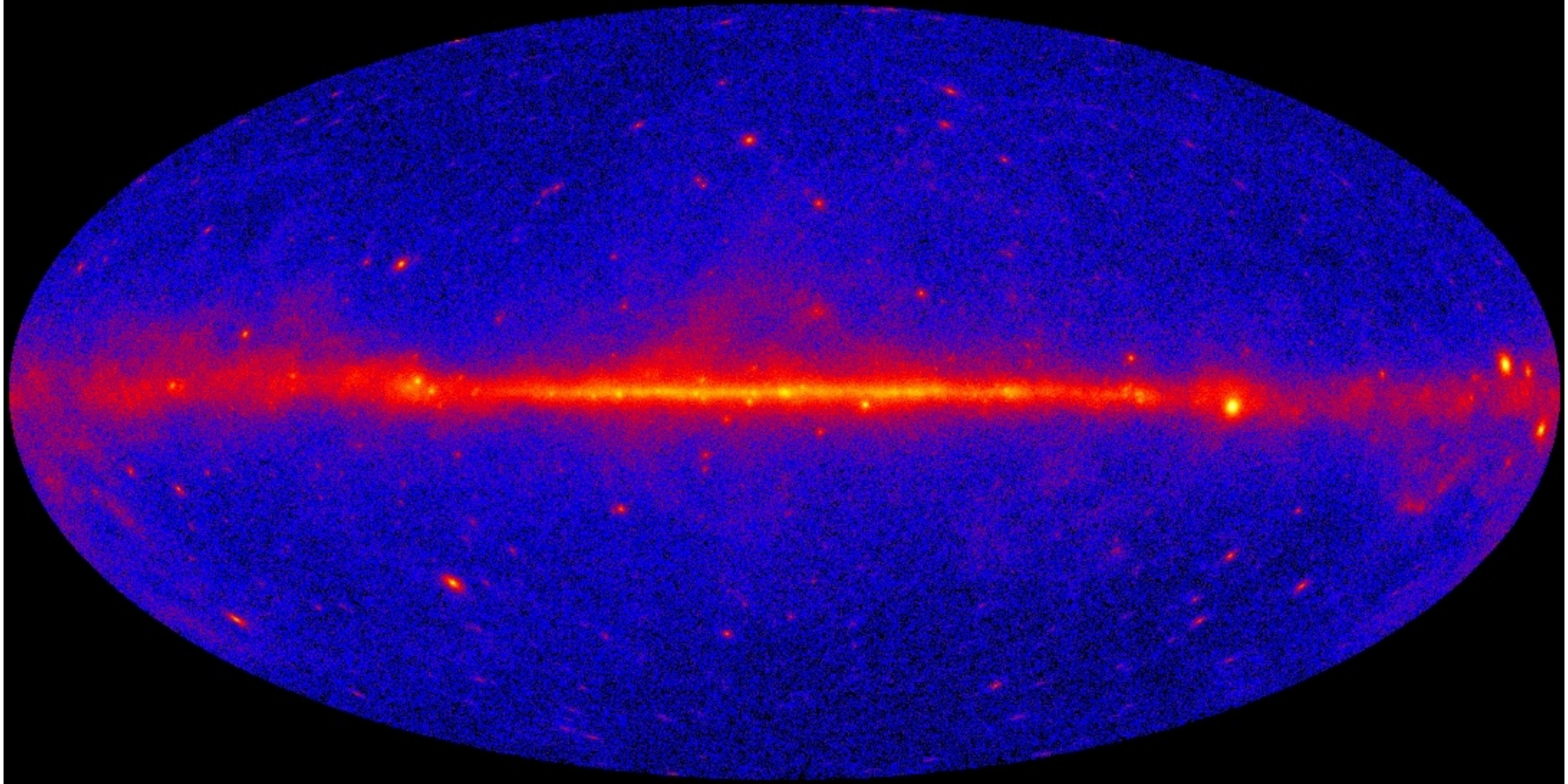
Springel et al ‘08

# The Milky Way seen in annihilation radiation

GALPROP, optimized



# The first-year all-sky image from Fermi



# Cold dark matter ?

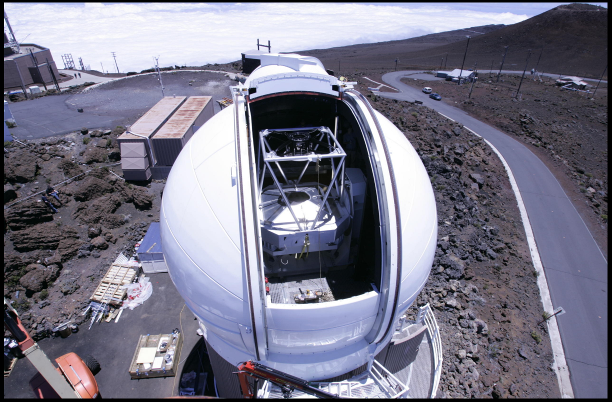
In CDM:

- Dark halos of all masses have “cuspy” density profiles, described by NFW form (to ~10 - 20%) or “Einasto” (to 5%)

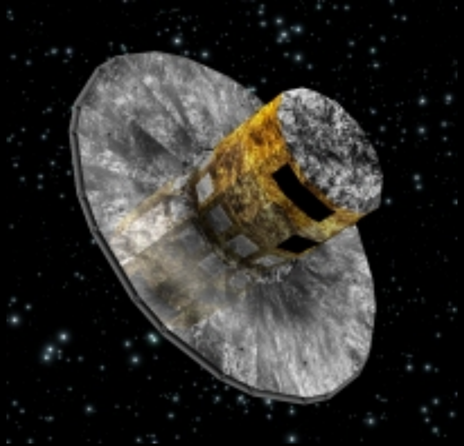
In the Milky Way

- Satellite data (photo/kinematics) consistent with predicted cusps
- No. of satellites (“satellite problem”) explained by gal formation
- Stellar streams (e.g Sag.) consistent with hierarchical formation

Milky Way



Pan-starrs: will discover (many?) new satellites



Gaia will make a 3D map of the Milky Way

ICC
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# Conclusions: CDM detection

- Many small substructures, with convergent mass fraction
  - DM distribution not fractal nor dominated by Earth-mass objects

- $\gamma$-ray annihilation may be detectable by FERMI which should:
  - First detect smooth halo (unless $\sigma v \neq$ const. )
  - Then (perhaps) detect dark subhalos with no stars
  - Sub-substructure boost irrelevant for detection

- With more than 99.9% confidence the Sun lies in a region where the DM density differs from the smooth mean value by < 15%

- The local velocity distribution of DM particles is close to a trivariate Gaussian